Ref 2

(54) Title: FIBER OPTIC ROTATION SENSOR
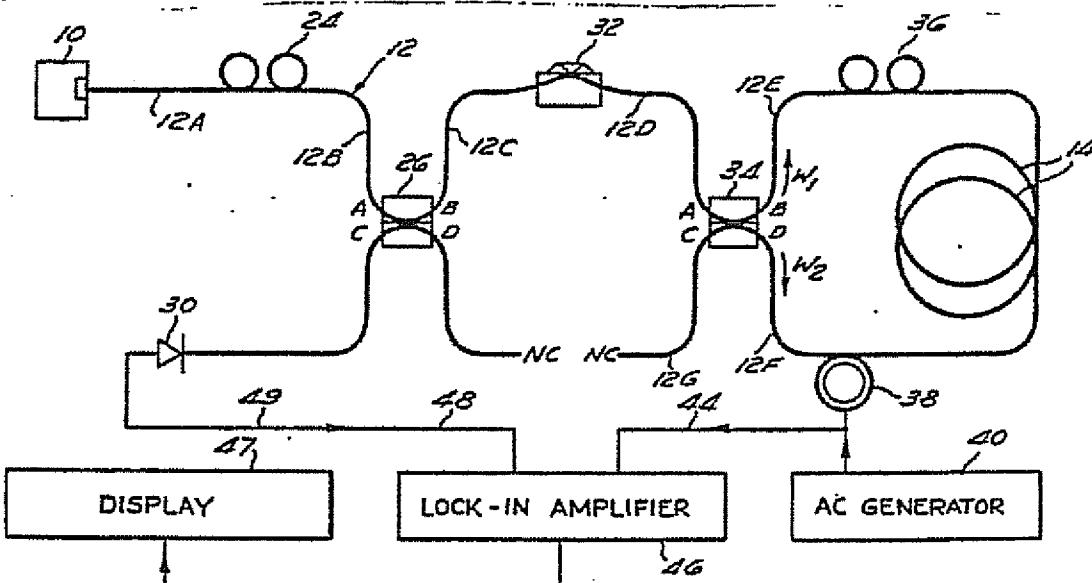
(57) Abstract

A fiber optic rotation sensor, employing the Sagnac effect, comprises all fiber optic components (24, 26, 32, 34, 36, 38), positioned along a continuous, uninterrrupted strand (12) of fiber optic material. The rotation sensor includes a detection system (30, 40, 46, 47) utilizing a modulator (38) for phase modulating light waves which counterpropagate through a loop (14) formed in the fiber optic strand (12). The modulator (38) is operated at a specific frequency to eliminate amplitude modulation in the detected optical output signal. The rotation sensor is mounted in a μ-metal housing (110) to shield it from the effects of ambient magnetic fields. An isolator (120) is utilized to prevent the optical output signal from return-ing to the laser source (10). This advantageously reduces power losses in the system by eliminating the need for a coupler to couple the output signal to a detector (30).

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FIBER OPTIC ROTATION SENSOR
Background of the Invention

The present invention relates to rotation sensors,
such as for use in gyroscopes, and particularly to a
5   fiber optic rotation sensor.

Fiber optic rotation sensors typically comprise a
loop of fiber optic material to which light waves are
coupled for propagation around the loop in opposite
directions. Rotation of the loop creates a relative
10 phase difference between counterpropagating waves, in
accordance with the well known "Sagnac effect," with the
amount of phase difference corresponding to the velocity
of rotation. The counterpropagating waves, when
recombined, interfere constructively or destructively to
15 produce an optical output signal which varies in
intensity in accordance with the rotation rate of the
loop. Rotation sensing is commonly accomplished by
detection of this optical output signal.

Systems of this type have heretofore employed bulk
20 optical components for processing and directing the
light applied to the sensing loop. While these devices
provide a substantial improvement over other types of
rotation sensors, they are subject to certain
limitations and other disadvantages. For example, the
25 various system components must be aligned with each
other within very close tolerances for the system to
function properly. This critical alignment is often
difficult to establish and maintain, particularly where
the system is subjected to mechanical vibration, thermal
30 changes, and other physical disturbances.

Rotation sensors utilizing the Sagnac effect for
rotation sensing typically require a compensating system
to provide operating stability. One type of
compensating system is described by R. Ulrich in an
35 article entitled "Fiber Optic Rotation Sensing with Low
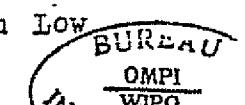
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Drift" (Optics Letters, May 1980, Vol. 5, No. 5). This
approach involves modulating the counter propagating
light waves and detecting the optical output wave at the
modulation frequency. However, such modulation, due to
5 imperfections in the modulator, tends to produce
amplitude modulation in the counter propagating waves
and thus, in the optical output signal. This amplitude
modulation may be caused directly by the modulating
device, or it may be a manifestion of polarization
10 modulation caused by the mechanical action of the
modulating device upon the fiber. In any event, such
amplitude modulation is disadvantageous since it
distorts the optical output signal, and thus, decreases
the accuracy of the rotation sensor.

15   Summary of the Invention
      The present invention solves these and other
problems of the prior art by providing an all fiber
optic rotation sensor in which the sensing loop and the
components for guiding and processing the light are
20 positioned or formed along a continuous, uninterrupted
strand of fiber optic material. Alignment problems are
thereby reduced or eliminated, and therefore, the
rotation sensor of the present invention is relatively
rugged and insensitive to mechanical shock, as compared
25 to prior art sensors utilizing bulk optical components.
      The rotation sensor comprises all fiber optic
components, such as a fiber optic directional coupler
which (a) splits the light from the source into two
waves that propagate around the sensing loop in opposite
30 directions, and (b) combines the counter propagating
  waves to provide an optical output signal. Proper
polarization of the applied light, the counter
propagating waves, and the optical output signal is
established, controlled, and maintained by a fiber optic
35 polarizer and fiber optic polarization controllers. A

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second fiber optic coupler is provided to couple the
optical output signal from the continuous strand to a
photo detector which outputs an electrical signal that
is proportional to the intensity of the optical signal.

5   Improved operating stability and sensitivity of the
rotation sensor is achieved by phase modulating the
counter propagating waves and utilizing a synchronous
detection system to measure the first harmonic of the
optical output signal intensity. In the detection system
10 disclosed, the amplitude of this first harmonic is
proportional to the rotation rate of the loop, and thus,
measurement of such first harmonic provides a direct
indication of the rotation rate of the loop.

       It has been found that amplitude modulation in odd
15 harmonics of the optical output signal, caused by the
phase modulator (either directly or indirectly, through
polarization modulation), may be eliminated by operating
the phase modulator at a specific frequency. Since the
detection system utilized detects only an odd harmonic
20 (e.g., the first harmonic), the effects of phase
modulator induced amplitude modulation may be eliminated
by operating at such frequency. This eliminates a
significant source of error in rotation sensing, and
thereby increases the accuracy of the rotation sensor.

25   While the detection system utilized in the present
invention significantly improves rotation sensing
accuracy, it has been found that other sources of error
in rotation sensing can limit the effectiveness of the
detection system. One such source of error is caused by
30 ambient magnetic fields, such as the earth's magnetic
field. These ambient magnetic fields induce a phase
difference between the counter-propagating waves, via
the Faraday effect, which can affect the intensity of
the optical output signal. In the present invention,
35 the effects of ambient magnetic fields are reduced or

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eliminated by placing the rotation sensor in a housing, comprised of material having a relatively high magnetic permeability, to effectively shield the rotation sensor from the magnetic environment.

5   The present invention utilizes an optical isolator to prevent the optical output signal from returning to the light source. Advantageously, use of this optical isolator eliminates the need for a coupler to couple the optical output signal from the continuous fiber strand.
10   Elimination of this coupler reduces system losses substantially, and thereby increases the intensity of the optical output signal at the detector.

          In the embodiment described herein, the effects of backscattering are reduced by utilizing a second phase
15   modulator to modulate the light applied to the fiber to reduce the coherence between backscattered light and the counter propagating waves. Alternatively, such backscatter effects may be reduced by utilizing a light source having a relatively short coherence length.

20   Brief Description of the Drawings
          These and other advantages of the present invention are best understood with reference to the drawings in which:

          FIGURE 1 is a schematic drawing of the rotation
25   sensor of the present invention showing the fiber optic components positioned along a continuous, uninterrupted strand of fiber optic material, and further showing the signal generator, photo detector, lock-in amplifier, and display associated with the detection system;

30   FIGURE 2 is a sectional view of one embodiment of a fiber optic directional coupler for use in the rotation sensor of Figure 1;

          FIGURE 3 is a sectional view of one embodiment of a fiber optic polarizer for use in the rotation sensor of
35   Figure 1;

FIGURE 4 is a perspective view of one embodiment of a fiber optic polarization controller for use in the rotation sensor of Figure 1;

FIGURE 5 is a schematic diagram of the rotation sensor of figure 1 with the polarizer, polarization controllers, and phase modulator removed therefrom;

FIGURE 6 is a graph of the intensity of the optical output signal, as measured by the photo detector, as a function of the rotationally induced SAGNAC phase difference, illustrating the effects of birefringence induced phase differences and birefringence induced amplitude fluctuations;

FIGURE 7 is a graph of phase difference as a function of time showing the phase modulation of each of the counterpropagating waves and the phase difference between the counterpropagating waves;

FIGURE 8 is a schematic drawing illustrating the effect of the phase modulation upon the intensity of the optical output signal, as measured by the detector, when the loop is at rest;

FIGURE 9 is schematic drawing showing the effect of the phase modulation upon the intensity of the optical output signal, as measured by the detector, when the loop is rotating;

FIGURE 10 is a graph of the amplifier output signal as a function of the rotationally induced SAGNAC phase difference, illustrating an operating range for the rotation sensor of Figure 1;

FIGURE 11 is a simplified schematic drawing of the loop portion of the rotation sensor of Figure 1, for illustrating the effect of the earth's magnetic field on the counter-propagating waves;

FIGURE 12 is a schematic drawing of a housing for enclosing the sensing loop to shield it from ambient magnetic fields;

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FIGURE 13 is a schematic drawing of the rotation
sensor of Figure 1 with an optical isolator included to
prevent the optical output signal from reaching the
light source, and showing the photodetector positioned
5   to detect the light rejected by the isolator so that a
coupler is not needed to extract the optical output
signal from the continuous fiber strand;

FIGURE 14 is a schematic diagram of the light source
and optical isolator showing the effect of the isolator
10   upon light propagating from the source towards the
sensing loop;

FIGURE 15 is a schematic diagram, similar to that of
Figure 14, showing the effect of the optical isolator on
the optical output signal as it returns from the loop
15   and propagates towards the source;

FIGURE 16 is a perspective view showing the
preferred manner of wrapping an optical fiber to form a
magneto-optic rotator; and

FIGURE 17 is a schematic drawing of one embodiment
20   of a magneto-optic rotator for use in the optical
isolator shown in Figure 13.

Detailed Description of the Preferred Embodiment

As shown in Figure 1, the rotation sensor of the
present invention comprises a light source 10 for
25   introducing light into a continuous length or strand of
optical fiber 12, a portion of which is wound into a
sensing loop 14. As used herein, the reference numeral
12 designates generally the entire continuous strand of
optical fiber, while the numeral 12 with letter suffixes
30   (A, B, C, etc.) designates portions of the optical fiber
12.

In the embodiment shown, the light source 10
comprises a galuim arsenide (GaAs) laser which produces
light having a wave length on the order of 0.82
35   microns. By way of specific example, the light source

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10 may comprise a model GO-DIP laser diode, commercially
available from General Optronics Corp., 3005 Hadley Rd.,
South Plainfield, New Jersey. The fiber optic strands,
such as the strand 12, are preferably single mode fibers
5   having, for example, an outer diameter of 80 microns and
a core diameter of 4 microns. The loop 14 comprises a
plurality of turns of the fiber 12, wrapped about a
spool or other suitable support (not shown). By way of
specific example, the loop 14 may have approximately
10   1000 turns of fiber wound on a form having a diameter of
14 centimeters.

Preferably, the loop 14 is wound symmetrically,
starting from the center, so that symmetrical points in
the loop 14 are in proximity. Specifically, the fiber
15   is wrapped about the spool so that the turns of the
central portion of the loop 14 are positioned innermost
adjacent to the spool and the turns toward the ends of
the loop are positioned outermost away from the spool so
that both end portions of the fiber loop 14 are
20   positioned symmetrically about the central turns and are
freely accessible at the outside of the loop 14. It is
believed that this reduces the environmental sensitivity
of the rotation sensor, since such symmetry causes time
varying temperature and pressure gradients to have a
25   similar effect on both of the counterpropagating waves.

Light from the source 10 is optically coupled to one
end of the fiber 12 by butting the fiber 12 against the
light source 10. Various components for guiding and
processing the light are positioned or formed at various
30   locations along the continuous strand 12. For the
purpose of describing the relative locations of these
components, the continuous fiber 12 will be described as
being divided into seven portions, labeled 12A through
12G, respectively, with the portion 12A through 12E
35   being on the side of the loop 14 that is coupled to the

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source 10, and the portions 12F and 12G being on the
opposite side of the loop 14.

Adjacent to the light source 10, between the fiber
portions 12A and 12B is a polarization controller 24. A
5   suitable type of polarization controller for use as the
controller 24 is described in the 25 September 1980
issue of Electronics Letters (Vol. 16, No. 20). A
description of the polarization controller 24 will be
provided subsequently, however, it should be presently
10 understood that this controller 24 permits adjustment of
both the state and direction of polarization of the
applied light.

The fiber 12 then passes through ports, labeled A
and B, of a directional coupler 26, located between the
15 fiber portions 12B and 12C, for coupling optical power
to a second strand of optical fiber 28 which passes
through the ports labeled C and D of the coupler 26, the
port C being on the same side of the coupler as the port
A, and the port D being on the same side of the coupler
20 as the port B. The end of the fiber 28 extending from
the port D terminates non-reflectively at the point
labeled "NC" (for "not connected") while the end of the
fiber 28 extending from the port C is optically coupled
to a photodetector 30. By way of specific example, the
25 photo detector 30 may comprise a standard, reverse
biased, silicon, PIN-type, photo diode. A coupler
suitable for use in the present invention is described
in detail in the 27 March 1980 issue of Electronics
Letters (Vol. 16, No. 7).

30 The fiber portion 12C, extending from the port B of
the coupler 26 passes through a polarizer 32, located
between the portions 12C and 12D. The polarizer 32
permits passage of light in one of the polarization
modes of the fiber 12, while preventing passage of light
35 in the other polarization mode. Preferably, the

polarization controller 24 is utilized to adjust the polarization of the applied light so that such polarization is substantially the same as that passed by the polarizer 32. This reduces loss of optical power as
5   the applied light propagates through the polarizer. A suitable type of polarizer for the use in the present invention is described in the November 1980 issue of Optics Letters (Vol. 5, No. 11).

After passing through the polarizer 32, the fiber 12
10   passes through ports, labeled A and B, of a directional coupler 34, located between the fiber portions 12D and 12E. This coupler 34 is preferably of the same type as described above in reference to the coupler 26. The fiber 12 is then wound into the loop 14, with a
15   polarization controller 36 located between the loop 14 and fiber portion 12F. This polarization controller 36 may be of the type discussed in reference to the controller 24, and is utilized to adjust the polarization of the waves counterpropagating through the
20   loop 14 so that the optical output signal, formed by superposition of these waves, has a polarization which will be efficiently passed, with minimal optical power loss, by the polarizer 32. Thus, by utilizing both the polarization controllers 24, 36, the polarization of the
25   light propagating through the fiber 12 may be adjusted for maximum optical power.

A modulator 38, driven by an AC generator 40, and connected thereto by a line 39, is mounted on the fiber 12, between the loop 14 and the fiber portion 12F. This
30   modulator 38 comprises a PZT cylinder, around which the fiber 12 is wrapped. The fiber 12 is bonded to the cylinder so that when it expands radially in response to the modulating signal from the generator 40, it stretches the fiber 12. An alternative type of
35   modulator (not shown), suitable for use with the present

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invention, comprises a PZT cylinder which longitudinally
stretches four segments of the fiber 12 bonded to short
lengths of capillary tubing at the ends of the
cylinder. Those skilled in the art will recognize that
5   this alternative type of modulator may impart a lesser
degree of polarization modulation to the propagating
optical signal than the modulator 38, however, it will
be seen subsequently that the modulator 38 may be
operated at a frequency which eliminates the undesirable
10 effects of polarization modulation. Thus, either type
of modulator is suitable for use in the present
invention.

The fiber 12 then passes through ports, labeled C
and D of the coupler 34, with the fiber portion 12F
15 extending from the port D and the fiber portion 12G
extending from the port C. Fiber portion 12G terminates
non-reflectively at a point labeled "NC" (for "not
connected"). The output signal from the AC generator 40
is supplied on a line 44 to a lock-in amplifier 46,
20 which also is connected to receive the output of the
photodetector 30 by a line 48. This signal to the
amplifier 46 provides a reference signal for enabling
the amplifier 46 to synchronously detect the detector
output signal at the modulation frequency. Thus, the
25 amplifier 46 effectively provides a band pass filter at
the fundamental frequency (i.e., first harmonic) of the
modulator 38, blocking all other harmonics of this
frequency. It will be seen below that the magnitude of
this first harmonic component of the detector output
30 signal is proportional, through an operating range, to
the rotation rate of the loop 14. The amplifier 46
outputs a signal, which is proportional to this first
harmonic component, and thus provides a direct
indication of the rotation rate, which may be visually
35 displayed on a display panel 47 by supplying the
amplifier output signal to the display 47 on a line 49.

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The Couplers 26 and 34

A preferred fiber optic directional coupler for use
as the couplers 26 and 34 in the rotation sensor or
gyroscope of the present invention is illustrated in
5 Figure 2. The coupler includes two strands 50A and 50B
of a single mode fiber optic material mounted in
longitudinal arcuate grooves 52A and 52B, respectively,
formed in optically flat, confronting surfaces of
rectangular bases or blocks 53A and 53B, respectively.
10 The block 53A with the strand 50A mounted in the groove
52A will be referred to as the coupler half 51A, and the
block 53B with the strand 50B mounted in the groove 52B
will be referred to as the coupler half 51B.

The arcuate grooves 52A and 52B have a radius of
15 curvature which is very large compared to the diameter
of the fibers 50, and have a width slightly larger than
the fiber diameter to permit the fibers 50, when mounted
therein, to conform to a path defined by the bottom
walls of the grooves 52. The depth of the grooves 52A
20 and 52B varies from a minimum at the center of the
blocks 53A and 53B, respectively, to a maximum at the
edges of the blocks 53A and 53B, respectively. This
advantageously permits the fiber optic strands 50A and
50B, when mounted in the grooves 52A and 52B,
25 respectively, to gradually converge toward the center
and diverge toward the edges of the blocks 53A, 53B,
thereby eliminating any sharp bends or abrupt changes in
direction of the fibers 50 which may cause power loss
through mode perturbation. In the embodiment shown, the
30 grooves 52 are rectangular in cross-section, however, it
will be understood that other suitable cross-sectional
contours which will accommodate the fibers 50 may be
used alternatively, such as a U-shaped cross-section or
a V-shaped cross-section.

35   At the centers of the blocks 53, in the embodiment
shown, the depth of the grooves 52 which mount the

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strands 50 is less than the diameter of the strands 50, while at the edges of the blocks 53, the depth of the grooves 52 is preferably at least as great as the diameter of the strands 50. Fiber optic material was
5 removed from each of the strands 50A and 50B, e.g. by lapping, to form respective oval-shaped planar surfaces, which are coplanar with the confronting surfaces of the blocks 53A, 53B. These oval surfaces, where the fiber optic material has been removed, will be referred to
10 herein as the fiber "facing surfaces". Thus, the amount of fiber optic material removed increases gradually from zero towards the edges of the blocks 53 to a maximum towards the center of the blocks 53. This tapered removal of the fiber optic material enables the fibers
15 to converge and diverge gradually, which is advantageous for avoiding backward reflection and excess loss of light energy.

In the embodiment shown, the coupler halves 51A and 51B are identical, and are assembled by placing the
·20 confronting surfaces of the blocks 53A and 53B together, so that the facing surfaces of the strands 50A and 50B are in facing relationship.

An index matching substance (not shown), such as index matching oil, is provided between the confronting
25 surfaces of the blocks 53. This substance has a refractive index approximately equal to the refractive index of the cladding, and also functions to prevent the optically flat surfaces 14 from becoming permanently locked together. The oil is introduced between the
30 blocks 53 by capillary action.

An interaction region 54 is formed at the junction of the strands 50, in which light is transferred between the strands by evanescent field coupling. It has been found that, to ensure proper evanescent field coupling,
35 the amount of material removed from the fibers 50 must

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be carefully controlled so that the spacing between the
core portions of the strands 50 is within a
predetermined "critical zone". The evanescent fields
extend into the cladding and decrease rapidly with
5   distance outside their respective cores. Thus,
sufficient material should be removed to permit each
core to be positioned substantially within the
evanescent field of the other. If too little material
is removed, the cores will not be sufficiently close to
10 permit the evanescent fields to cause the desired
interaction of the guided modes, and thus, insufficient
coupling will result. Conversely, if too much material
is removed, the propagation characteristics of the
fibers will be altered, resulting in loss of light
15 energy due to mode perturbation. However, when the
spacing between the cores of the strands 50 is within
the critical zone, each strand receives a significant
portion of the evanescent field energy from the other
strand, and good coupling is achieved without
20 significant energy loss. The critical zone includes
that area in which the evanescent fields of the fibers
50A and 50B overlap with sufficient strength to provide
coupling, i.e., each core is within the evanescent field
of the other. However, as previously indicated, mode
25 perturbation occurs when the cores are brought too close
together. For example, it is believed that, for weakly
guided modes, such as the HE_{11} mode in single mode
fibers, such mode perturbation begins to occur when
sufficient material is removed from the fibers 50 to
30 expose their cores. Thus, the critical zone is defined
as that area in which the evanescent fields overlap with
sufficient strength to cause coupling without
substantial mode perturbation induced power loss.

The extent of the critical zone for a particular
35 coupler is dependent upon a number of interrelated

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factors such as the parameters of the fiber itself and
the geometry of the coupler. Further, for a single mode
fiber having a step-index profile, the critical zone can
be quite narrow. In a single mode fiber coupler of the
5   type shown, the required center-to-center spacing
between the strands 50 at the center of the coupler is
typically less than a few (e.g., 2-3) core diameters.

Preferably, the strands 50A and 50B (1) are
identical to each other; (2) have the same radius of
10   curvature at the interaction region 54; and (3) have an
equal amount of fiber optic material removed therefrom
to form their respective facing surfaces. Thus, the
fibers 50 are symmetrical, through the interaction
region 54, in the plane of their facing surfaces, so
15   that their facing surfaces are coextensive if
superimposed. This ensures that the two fibers 50A and
50B will have the same propagation characteristics at
the interaction region 54, and thereby avoids coupling
attenuation associated with dissimilar propagation
20   characteristics.

The blocks or bases 53 may be fabricated of any
suitable rigid material. In one presently preferred
embodiment, the bases 53 comprise generally rectangular
blocks of fused quartz glass approximately 1 inch long,
25   1 inch wide, and 0.4 inch thick. In this embodiment,
the fiber optic strands 50 are secured in the slots 52
by suitable cement, such as epoxy glue. One advantage
of the fused quartz blocks 53 is that they have a
coefficient of thermal expansion similar to that of
30   glass fibers, and this advantage is particularly
important if the blocks 53 and fibers 50 are subjected
to any heat treatment during the manufacturing process.
Another suitable material for the block 53 is silicon,
which also has excellent thermal properties for this
35   application.

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The coupler includes four ports, labeled A, B, C and
D in Figure 2. When viewed from the perspective of
Figure 2, ports A and C, which correspond to strands 50A
and 50B, respectively, are on the left-hand side of the
5 coupler, while the ports B and D, which correspond to
the strands 50A and 50B, respectively, are on the
right-hand side of the coupler. For the purposes of
discussion, it will be assumed that input light is
applied to port A. This light passes through the
10 coupler and is output at port B and/or port D, depending
upon the amount of power that is coupled between the
strands 50. In this regard, the term "normalized
coupled power" is defined as the ratio of the coupled
power to the total output power. In the above example,
15 the normalized coupled power would be equal to the ratio
of the power at port D to the sum of the power output at
ports B and D. This ratio is also referred to as the
"coupling efficiency", and when so used is typically
expressed as a percent. Thus, when the term "normalized
20 coupled power" is used herein, it should be understood
that the corresponding coupling efficiency is equal to
the normalized coupled power times 100. In this regard,
tests have shown that the coupler of the type shown in
Figure 2 has a coupling efficiency of up to 100%.
25 However, the coupler may be "tuned" to adjust the
coupling efficiency to any desired value between zero
and the maximum, by offsetting the facing surfaces of
the blocks 53. Such tuning is preferably accomplished
by sliding the blocks 53 laterally relative to each
30 other.

The coupler is highly directional, with
substantially all of the power applied at one side of
the coupler being delivered to the other side of the
coupler. That is, substantially all of the light
35 applied to input Port A is delivered to the output Ports

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B and D, without contra-directional coupling to Port C.
Likewise, substantially all of the light applied to
input Port C is delivered to the output Ports B and D.
Further, this directivity is symmetrical. Thus, light

5   supplied to either input Port B or input Port D is
delivered to the output Ports A and C. Moreover, the
coupler is essentially non-discriminatory with respect
to polarizations, and thus, preserves the polarization
of the coupled light. Thus, for example, if a light

10 beam having a vertical polarization is input to Port A,
the light coupled from Port A to Port D, as well as the
light passing straight through from Port A to Port B,
will remain vertically polarized.

From the foregoing, it can be seen that the coupler

15 may function as a beam-splitter to divide the applied
light into two counter-propagating waves W1, W2 (Figure
1). Further, the coupler may additionally function to
recombine the counter-propagating waves after they have
traversed the loop 14 (Figure 1).

20   In the embodiment shown, each of the couplers 26, 34
has a coupling efficiency of fifty percent, as this
choice of coupling efficiency provides maximum optical
power at the photodetector 30 (Figure 1). As used
herein, the term "coupling efficiency" is defined as the

25 power ratio of the coupled power to the total output
power, expressed as a percent. For example, referring
to Figure 2, if light is applied to Port A, the coupling
efficiency would be equal to the ratio of the power at
Port D to the sum of the power output at Ports B and D.

30 Further, a coupling efficiency of 50% for the coupler 34
insures that the counterpropagating waves W1, W2 are
equal in magnitude.

The Polarizer 32

A preferred polarizer for use in the rotation sensor

35 of Figure 1 is illustrated in Figure 3. This polarizer

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includes a birefringent crystal 60, positioned within
the evanescent field of light transmitted by the fiber
12. The fiber 12 is mounted in a slot 62 which opens to
the upper face 63 of a generally rectangular quartz
5   block 64. The slot 62 has an arcuately curved bottom.
wall, and the fiber is mounted in the slot 62 so that it
follows the, contour of this bottom wall. The upper
surface 63 of the block 64 is lapped to remove a portion
of the cladding from the fiber 12 in a region 67. The
10 crystal 60 is mounted on the block 64, with the lower
surface 68 of the crystal facing the upper surface 63 of
the block 64, to position the crystal 60 within the
evanescent field of the fiber 12.

    The relative indices of refraction of the fiber 12
15 and the birefringent material 60 are selected so that
the wave velocity of the desired polarization mode is
greater in the birefringent crystal 60 than in the fiber
12, while the wave velocity of an undesired polarization
mode is greater in the fiber 12 than in the birefringent
20 crystal 60. The light of the desired polarization mode
remains guided by the core portion of the fiber 12,
whereas light of the undesired polarization mode is
coupled from the fiber 12 to the birefringent crystal
60. Thus, the polarizer 32 permits passage of light in
25 one polarization mode, while preventing passage of light
in the other polarization mode. As previously
indicated, the polarization controllers 24, 36 (Figure
1) may be utilized to adjust the polarizations of the
applied light and optical output signal, respectively,
30 so that optical power loss through the polarizer is
minimized.

The Polarization Controllers 24, 36

    One type of polarization controller suitable for use
in the rotation sensor of Figure 1 is illustrated in
35 Figure 4. The controller includes a base 70 on which a

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plurality of upright blocks 72A through 72D are mounted. Between adjacent ones of the block 72, spools 74A through 74C are tangentially mounted on shafts 76A through 76C, respectively. The shafts 76 are axially
5   aligned with each other, and are rotatably mounted between the blocks 72. The spools 74 are generally cylindrical and are positioned tangentially to the shafts 76, with the axes of the spools 74 perpendicular to the axes of the shafts 76. The strand 12 extends
10 through axial bores in the shafts 76 and is wrapped about each of the spools 74 to form three coils 78A through 78C. The radii of the coil 78 are such that the fiber 12 is stressed to form a birefringent medium in each of the coils 78. The three coils 78A through 78C
15 may be rotated independently of each other about the axes of the shafts 74A through 74C, respectively, to adjust the birefringence of the fiber 12 and, thus, control the polarization of the light passing through the fiber 12.

20   The diameter and number of turns in the coil 78 are such that the outer coils 78A and C provide a spatial delay of one-quarter wavelength, while the central coil 78D provides a spatial delay of one-half wavelength. The quarter wavelength coils 78A and C control the
25 elipticity of the polarization, and the half wavelength coil 78B controls the direction of polarization. This provides a full range of adjustment of the polarization of the light propagating through the fiber 12. It will be understood, however, that the polarization controller
30 may be modified to provide only the two quarter wave coils 78A and C, since the direction of polarization (otherwise provided by the central coil 78B) may be controlled indirectly through proper adjustment of the elipticity of polarization by means of the two quarter
35 wave coils 78A and C. Accordingly, the polarization

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controllers 24 and 36 are shown in Figure 1 as including
only the two quarter wave coils 78A and C. Since this
configuration reduces the overall size of the
controllers 24-36, it may be advantageous for certain
5   applications of the present invention involving space
limitations.

Thus, the polarization controllers 24 and 36 provide
means for establishing, maintaining and controlling the
polarization of both the applied light and the
10 counter-propagating waves.

Operation Without Phase Modulation
or Polarization Control

In order to fully understand the function and
importance of the polarizer 32 (Figure 1) and phase
15 modulator 38, the operation of the rotation sensor will
first be described as if these components had been
removed from the system. Accordingly, Figure 5 shows
the rotation sensor of Figure 1, in schematic block
diagram form, with the modulator 38, polarizer 32, and
20 associated components removed therefrom.

Light is coupled from the laser source 10 to the
fiber 12 for propagation therethrough. The light enters
Port A of the coupler 26, where a portion of the light
is lost through Port D. The remaining portion of the
25 light propagates from Port B to Port A of the coupler
34, where it is split into two counter-propagating waves
W1, W2 of equal amplitude. The wave W1 propagates from
the Port B in a clockwise direction about the loop 14,
while the wave W2 propagates from Port D in a
30 counter-clockwise direction around the loop 14. After
the waves W1, W2 have traversed the loop 14, they are
recombined by the coupler 34 to form an optical output
signal, which propagates from Port A of the coupler 34
to Port B of the coupler 26. A portion of the optical
35 output signal is coupled from Port B to Port C of the

20

coupler 26 for propagation along the fiber 28 to the
photodetector 30. This photodetector 30 outputs an
electrical signal which is proportional to the intensity
of the light impressed thereon by the optical output
5   signal.

The intensity of the optical output signal will vary
in accordance with the amount and type (i.e.,
constructive or destructive) of interference between the
waves W1, W2 when they are recombined or super-posed at
10 the coupler 34. Ignoring, for the moment, the effects
of fiber birefringence, the waves W1, W2 travel the same
optical path around the loop 14. Thus, assuming the
loop 14 is at rest, when the waves W1, W2 are recombined
at the coupler 34, they will interfere constructively,
15 with no phase difference therebetween, and the intensity
of the optical output signal will be at a maximum.
However, when the loop 14 is rotated, the
counter-propagating waves W1, W2 will be shifted in
phase, in accordance with the Sagnac effect, so that
20 when they are superposed at the coupler 34, they
destructively interfere to reduce the intensity of the
optical output signal. Such Sagnac phase difference
between the waves W1, W2, caused by rotation of the loop
14, is defined by the following relationship:

25

$$\phi_{ws} = \frac{8\pi NA}{\lambda c} \Omega \qquad\qquad (1)$$

Where A is the area bounded by the loop 14 of
30 optical fiber, N is the number of turns of the optical
fiber about the area A, Ω is the angular velocity of the
loop about an axis which is perpendicular to the plane
of the loop, and λ and c are the free space values of
the wave length and velocity, respectively, of the light
35 applied to the loop.

21

The intensity of the optical output signal (I_T) is a function of the Sagnac phase difference (ϕ_{ws}) between the waves W1, W2, and is defined by the following equation:

5

$$I_T = I_1 + I_2 + 2\sqrt{I_1 I_2}\ \cos\phi_{ws}$$

(2)

10 where I_1 and I_2 are the individual intensities of the waves W1, W2, respectively.

From equations (1) and (2) it may be seen that the intensity of optical output signal is a function of the rotation rate (Ω). Thus, an indication of such 15 rotation rate may be obtained by measuring the intensity of the optical output signal, utilizing the detector 30.

Figure 6 shows a curve 80, which illustrates this relationship between the intensity of the optical output signal (I_T) and the Sagnac phase difference (ϕ_{ws}) 20 between the counter-propagating waves W1, W2. The curve 80 has the shape of a cosine curve, and the intensity of the optical output signal is at a maximum when the Sagnac phase difference (ϕ_{ws}) is zero.

If it is assumed that the only source of phase 25 difference between the counter-propagating waves W1, W2 is the rotation of the loop 14, the curve 80 will vary symmetrically about the vertical axis. However, in practice, a phase difference between the counter-propagating waves W1, W2 may be caused not only by 30 rotation of the loop 14, but also by the residual birefringence of the optical fiber 12. Birefringence-induced phase differences occur because fiber birefringence tends to cause each of the two polarization modes of the single mode fiber 12 to 35 propagate light at a different velocity. This creates a

22

non-reciprocal, non-rotationally induced phase difference between the waves W1, W2, which causes the waves W1, W2 to interfere in a manner that distorts or shifts the curve 80 of Figure 6, for example, as

5   illustrated by the curve 82, shown in phantom lines. Such birefringence-induced, non-reciprocal phase difference is indistinguishable from a rotationally-induced Sagnac phase difference, and is dependent on environmental factors which vary fiber birefringence,

10   such as temperature and pressure. Thus, fiber birefringence is the cause of a major source of error in fiber optic rotation sensors.

Operation with the Polarizer 32

     The problem of non-reciprocal operation due to fiber

15   birefringence is solved in the rotation sensor of the present invention by means of the polarizer 32 (Figure 1) which, as discussed above, permits utilization of only a single polarization mode. Thus, when the polarizer 32 is introduced into the system, at the point

20   designated by the reference numeral 84 in Figure 5, light input through the polarizer 32 propagates into the loop 14 in the desired polarization mode. Further, when the counterpropagating waves are recombined to form the optical output signal, any light that is not of the same

25   polarization as the light applied to the loop is prevented from reaching the photo detector 30, since the optical output signal as it travels from port A of coupler 34 to port B of coupler 26, also passes through the polarizer 32. Thus, the optical output signal, when

30   it reaches the detector 30, will have precisely the same polarization as the light applied to the loop. Therefore, by passing the input light and optical output signal through the same polarizer 32, only a single optical path is utilized, thereby eliminating the

35   problem of birefringence-induced phase difference.

Further, it should be noted that the polarization
controllers 24, 36 (Figure 1) may be used to adjust the
polarization of the applied light, and optical output
signal, respectively, to reduce optical power loss at
5 the polarizer 32, and thus, maximize the signal
intensity at the detector 30.

Operation with the Phase Modulator 38

Referring again to Figure 6, it will be seen that,
because the curve 80 is a cosine function, the intensity
10 of the optical output signal is nonlinear for small
phase differences (ϕ_{ws}) between the waves W1, W2.
Further, the optical output signal intensity is
relatively insensitive to changes in phase difference,
for small values of . ϕ_{ws}. Such nonlinearity and
15 insensitivity makes it difficult to transform the
optical intensity (I_T) measured by detector 30 into a
signal indicative of the rate of rotation Ω (equation
1) of the loop 14.

Further, although birefringence induced phase
20 differences between the waves W1, W2 are eliminated, as
discussed above, by use of the polarizer 32, cross
coupling between polarization modes caused by fiber
birefringence reduces the optical intensity of the
optical output signal, since such cross coupled light is
25 prevented from reaching the photodetector 30 by the
polarizer 32. Thus, changes in fiber birefringence
cause the amplitude of the curve 80 of Figure 6 to vary,
for example, as illustrated by the curve 84. It will be
understood that curves 80, 82, 84 of Figure 6 are not
30 drawn to scale.

The foregoing problems are solved in the rotation
sensor of the present invention by means of a
synchronous detection system utilizing the phase
modulator 38, signal generator 40 and lock-in amplifier
35 46, shown in Figure 1. Referring to Figure 7, the phase

24

modulator 38 modulates the phase of each of the
propagating waves W1, W2 at the frequency of the signal
generator 40. However, as may be seen from Figure 1,
the phase modulator 38 is located at one end of the loop
5   14. Thus, the modulation of the wave W1 is not
necessarily in phase with the modulation of the wave
W2. Indeed, it is necessary for proper operation of
this synchronous detection system that the modulation of
the waves W1, W2 be out of phase. Referring to Figure
10   7, it is preferable that the modulation of the wave W1,
represented by the sinusoidal curve 90, be 180 degrees
out of phase with the modulation of the wave W2,
represented by the curve 92. Use of a modulation
frequency which provides such 180 degree phase
15   difference between the modulation of the wave W1
relative to that of W2 is particularly advantageous in
that it eliminates modulator induced amplitude
modulation in the optical output signal measured by the
detector 30. This modulation frequency (f_m) may be
20   calculated using the following equation:

$$f_m = \frac{c}{2n_{eq}L} \qquad (3)$$

25

where L is the differential fiber length, between the
coupler 34 and modulator 38, for the counter propagating
waves W1, W2 (i.e., the distance, measured along the
fiber, between the modulator 38 and a symmetrical point
30   on the other side of the loop 14); n_{eq} is the
equivalent refractive index for the single mode fiber
12, and c is the free space velocity of the light
applied to the loop 14.

At this modulation frequency (f_m), the phase
35   difference (ϕ_{wm}) between the counter propagating

waves W1, W2, due to phase modulation of these waves in
accordance with the curves 90 and 92, is illustrated by
the sinusoidal curve 94 in Figure 7. This modulation of
the phase difference between the waves W1, W2 will
5   modulate the intensity (I_T) of the optical output
signal in accordance with the curve 80 of Figure 6,
since such phase modulation ϕ_{wm} is indistinguishable
from rotationally induced Sagnac phase differences ϕ_{ws}.

The foregoing may be understood more fully through
10 reference to Figures 8 and 9 which graphically
illustrate the effect of (a) the phase modulation ϕ_{wm},
defined by the curve 94 of Figure 7, and (b) the
Sagnac phase difference ϕ_{ws}, upon the intensity
(I_T) of the optical output signal, represented by the
15 curve 80 of Figure 6. However, before proceeding with a
discussion of Figures 7 and 8, it should first be
understood that the intensity (I_T) of the modulated
optical output signal is a function of the total phase
difference between the waves W1, W2. Further, such
20 total phase difference is comprised of both the
rotationally induced Sagnac phase difference ϕ_{ws} and
the time varying modulation induced phase difference ϕ_{wm}.
Thus, the total phase difference ϕ_w between the waves
W1, W2 may be expressed as follows:
25

$$\phi_w = \phi_{ws} + \phi_{wm}$$

(4)

Accordingly, since the effects of the modulation induced
30 phase difference ϕ_{wm}, as well as the rotationally
induced phase difference ϕ_{ws}, will be considered in
reference to Figures 8 and 9, the horizontal axis for
the curve 80 has been relabeled as ϕ_w to indicate
that the total phase difference is being considered,
35 rather than only the rotationally induced phase
difference, as in Figure 6.

26

Referring now to Figure 8, the effect of the phase
modulation ϕ_{wm} (curve 94) upon the intensity I_T of
the optical output signal (curve 80) will be discussed.
In Figure 8, it is assumed that the loop 14 is at rest,
5   and thus, the optical signal is not affected by the
Sagnac effect. Specifically, it may be seen that the
modulation induced phase difference curve 94 varies the
optical output signal in accordance with the curve 80,
symmetrically about its vertical axis, so that the
10   optical intensity measured by the detector 30 varies
periodically at a frequency equal to the second harmonic
of the modulating frequency, as shown by the curve 96.
Since, as discussed above, the lock-in amplifier 46 is
enabled by the signal generator 40 (Figure 1) to
15   synchronously detect the detector output signal at the
modulation frequency (i.e., first harmonic) of the
modulator 38, and since the detector output signal is at
the second harmonic of the modulation frequency as shown
by the curve 96, the amplifier output signal will be
20   zero and the display 47 will indicate a rotation rate of
zero. It should be noted that, even if birefringence
induced amplitude fluctuations occur in the optical
output signal, as discussed in reference to the curve 84
of Figure 6, the curve 96 of Figure 8 will remain at a
25   second harmonic frequency. Thus, such birefringence
induced amplitude fluctuations will not affect the
amplifier 46 output signal. The dectection system of
the   present   invention   therefore,   provides   a
substantially stable operating point that is insensitive
30   to changes in birefringence, particularly when the loop
14 is at rest.

When the loop 14 is rotated, the counter propagating
waves W1, W2 are shifted in phase, as discussed above,
in accordance with the Sagnac effect. The Sagnac phase
35   shift provides a phase difference ϕ_{ws} which adds to

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the phase difference ϕ_{wm} created by the modulator 38, so that the entire curve 94 is translated in phase from the position shown in Figure 8, by an amount equal to ϕ_{ws}, to the position shown in Figure 9. This causes the

5 optical output signal to vary non-symmetrically in accordance with the curve 80, thereby harmonically distorting this signal as shown by the curve 96 of Figure 9, so that it includes a component at the fundamental (i.e., first harmonic) frequency of the

10 modulator 38, as illustrated in phantom lines by the sinusoidal curve 98. It will be seen subsequently that the RMS value of this sinusoidal curve 98 is proportional to the sine of the rotationally induced, Sagnac phase difference ϕ_{ws}. Since the amplifier 46

15 synchronously detects signals having the fundamental frequency of the modulator 38, the amplifier 46 will output a signal to the display 47 that is proportional to the RMS value of the curve 98 to indicate the rotation rate of the loop.

20   The drawings of Figure 9 illustrate the intensity wave form of the optical output signal for one direction of rotation (e.g., clockwise) of the loop 14. However, it will be understood that, if the loop 14 is rotated in the opposite direction (e.g., counter-clockwise) at an

25 equal velocity, the intensity wave form 96 of the optical output signal will be exactly the same as illustrated in Figure 9, except that it will be translated so that the curve 98 is shifted 180 degrees from the position shown in Figure 9. The lock-in

30 amplifier 46 detects this 180 degree phase difference for the curve 98, by comparing its phase with the phase of the reference signal from the signal generator 40, to determine whether the rotation of the loop is clockwise or counter-clockwise. Depending on the direction of

35 rotation, the amplifier 46 outputs either a positive or

negative signal to the display 47. However, regardless
of the direction of rotation, the magnitude of the
signal is the same for equal rates of rotation of the
loop 14.

5   The wave form of the amplifier output signal is
shown in Figure 10 as the curve 100. It will be seen
that this curve 100 is sinusoidal and varies positively
or negatively from zero rotation rate depending on
whether the rotation of the loop 14 is clockwise or
10 counter clockwise. Further, the curve 100 has a
substantially linear portion 102 which varies
symmetrically about the origin and provides a relatively
wide operating range for measuring rotation. Moreover,
the slope of the curve 100 provides excellent
15 sensitivity throughout its linear operating range 102.

       Thus, by utilizing the synchronous detection system,
the above described problems of non-linearity,
insensitivity, and birefringence induced amplitude
fluctuations are reduced or eliminated.

20   A further advantage of this detection system relates
to the fact that state of the art phase modulators, such
as the modulator 38, induce amplitude modulation in the
optical output signal, either directly, or indirectly
through polarization modulation. However, it will be
25 recalled from the discussion in reference to equation 3
that, by operating at a specific frequency at which the
phase difference between the modulation of the waves W1
and W2 is 180 degrees, the odd harmonic frequency
components of the amplitude modulation, that are induced
30 in each of the counter propagating waves, W1, W2 by the
modulator 38, cancel each other when the waves are
superposed to form the optical output signal. Thus,
since the above described detection system detects only
an odd harmonic (i.e., the fundamental frequency) of the
35 optical output signal, the effects of amplitude

modulation are eliminated. Therefore, by operating at
the specific frequency defined by equation 3, and
detecting only an odd harmonic of the optical output
signal, the rotation sensor of the present invention may
5   operate independently of modulator induced amplitude and
polarization modulation.

A further benefit of operating at the specific
frequency is that even harmonics of the phase
modulation, induced by the modulator 38 in each of the
10   counter propagating phase W1, W2, cancel when these
waves are superposed to form the optical output signal.
Since these even harmonics may produce spurious odd
harmonics in the optical output signal which might
otherwise be detected by the detection system, their
15   elimination improves the accuracy of rotation sensing.

In addition to operating the phase modulator 38 at
the frequency defined by equation 3, it is also
preferable to adjust the magnitude of the phase
modulation so that the amplitude of the detected first
20   harmonic of the optical output signal intensity is
maximized, since this provides improved rotation sensing
sensitivity and accuracy. It has been found that the
first harmonic of the optical output signal intensity is
at the maximum, for a given rotation rate, when the
25   amplitude of the modulator induced phase difference
between the waves W1, W2, indicated by the dimension
labeled z in Figure 7, 8 and 9, is 1.84 radians. This
may be understood more fully through reference to the
following equation for the total intensity (I_T) of two
30   superposed waves having individual intensities of I_1
and I_2, respectively, with a phase difference ϕ_w
therebetween.

where:

$$I_T = I_1 + I_2 + 2 \sqrt{I_1 I_2} \, \cos \phi_w \qquad (5)$$

35

$$\phi_w = \phi_{ws} + \phi_{wm} \qquad (6)$$

30

and

$$\phi_{wm} = z \sin(2\pi f_m t) \qquad (7)$$

Thus,

$$\phi_w = \phi_{ws} + z \sin(2\pi f_m t) \qquad (8)$$

5   the Fourier expansion of cosine ϕ_w is:

$$\cos \phi_w = \cos \phi_{ws} \{ J_0(z) + 2 \sum_{n=1}^{\infty} J_{2n}(z) \cos[2\pi (2nf_m t)] \}$$

10

$$-\sin \phi_{ws} \{ 2 \sum_{n=1}^{\infty} J_{2n-1}(z) \sin[2\pi (2n-1) f_m t] \} \qquad (9)$$

where $J_n(z)$ is the nth Bessel function of the
15   variable z, and z is the peak amplitude of the modulator
induced phase difference between the waves W1, W2.

Therefore, detecting only the first harmonic of I_T
yields:

$$I_{T(1)} = 4 \sqrt{I_1 I_2} \; J_1(z) \sin \phi_{ws} \sin(2\pi f_m t)$$

20   (10)

Thus, the amplitude of the first harmonic of the
optical output signal intensity is dependent upon the
value of the first Bessel function $J_1(z)$. Since
$J_1(z)$ is a maximum when z equals 1.84 radians, the
25   amplitude of the phase modulation should preferably be
selected so that the magnitude of the modulator induced
phase difference (z) between the waves W1, W2 is 1.84
radians.

Reducing the Effects of Backscatter

30   As is well known, present state of the art optical
fibers are not optically perfect, but have imperfections
which cause scattering of small amounts of light. This
phenomena is commonly referred to as rayleigh
scattering. Although such scattering causes some light
35   to be lost from the fiber, the amount of such loss is

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relatively small, and therefore, is not a major
concern. The principle problem associated with rayleigh
scattering relates not to scattered light which is lost,
but rather, to light which is reflected so that it
5   propagates through the fiber in a direction opposite to
its original direction of propagation. This is commonly
referred to as "backscattered" light. Since such
backscattered light is coherent with the light
comprising the counterpropagating waves, W1, W2, it can
10 constructively or destructively interfere with such
propagating waves, and thereby cause "noise" in the
system, i.e. cause spurious variations in the intensity
of the optical output signal, as measured by the
detector 30.

15   The portion of backscattered light from one wave
which will be coherent with the counterpropagating wave
is that which is scattered within a coherence length of
the center of the loop 14. Thus, by reducing the
coherence length of the source, the coherence between
20 the backscattered light and the counterpropagating waves
is reduced. The remaining portion of the backscattered
light will be incoherent with the counterpropagating
wave, and thus, the interference therebetween will vary
randomly so that it is averaged. Therefore, this
25 incoherent portion of the backscattered light will be of
substantially constant intensity, and consequently, it
will not cause significant variations in the intensity
of the optical output signal. Accordingly, in the
present invention, the effects of backscattered light
30 are reduced by utilizing, as the light source 10, a
laser having a relatively short coherence length, for
example, one meter or less. By way of specific example,
the light source 10 may comprise the model GO-DIP laser
diode, commercially available from General Optronics
35 Corp., as mentioned above.

32

An alternative method of prohibiting destructive or constructive interference between the backscattered waves and the propagating waves involves the inclusion of an additional phase modulator (not shown) in the

5   system at the center of the fiber loop 14. This phase modulator is not synchronized with the modulator 38.

The propagating waves will pass through this additonal phase modulator one time only, on their travel around the loop. For backscatter which occurs from a

10 propagating wave before the wave reaches the additional modulator, the backscatter will not be phase modulated by this additional modulator, since neither its source propagating wave nor the backscatter itself has passed through the additional modulator.

15 On the other hand, for backscatter which occurs from a propagating wave after the wave passes through this additional phase modulator, the backscatter will be effectively twice phase modulated, once when the propagating wave passed through the additional phase

20 modulator, and once when the backscatter passed through the additional modulator.

Thus, if the additional phase modulator introduces a phase shift of $\phi(t)$, the backscattered wave originating at any point except at the center of the

25 loop 14 will have a phase shift of either zero, or 2 $\phi(t)$, either of which is time varying with respect to the $\phi(t)$ phase shift for the propagating wave. This time varying interference will average out over time, effectively eliminating the effects of the backscattered light.

30 In yet another alternative method of prohibiting destructive or constructive interference from backscattered light, the additional phase modulator, not synchronized with the modulator 38, may be introduced at the output of the light source 10.

35 In this case, backscatter occurring at any point other than the center of the loop 14 will have a

33

different optical path length from the light source 10 to the detector 30 than does the propagating wave from which the backscattered light originated.

5   Thus, the propagating wave will traverse the loop 14 one time, while the backscattered wave, and the propagating wave from which it originated, will have traversed a portion of the loop 14 twice. If this portion is not one half of the loop, the path lengths differ.

10   Because the path lengths differ, a propagating wave which reaches the detector 30 must have been generated at the source 10 at a different time than a backscattered wave which reaches the detector 30 simultaneously.

15   The phase shift introduced by the additional phase modulator at the source 10 introduces a phase shift $\phi(t)$ to the propagating wave, but a phase shift of $\phi(t + k)$ to the backscattered wave, where K is the time difference between the passage of the waves through the loop 14.

20   Since $\phi(t + k)$ is time varying with respect to $\phi(t)$, the backscattered interference will average out over time, effectively eliminating the effects of the backscatter.

Reducing the Effects of Ambient Magnetic Fields

It has been found that ambient magnetic fields, such

25   as the earth's magnetic field, can limit the rotation sensing accuracy of the present invention by inducing a phase difference between the counter-propagating waves W1, W2. Such magnetic fields induce this phase difference by causing the respective phases of each of the two

30   counter-propagating waves W1, W2 to be shifted in opposite directions relative to each other, causing one to lead and one to lag.

These phase shifts of the waves W1, W2 are due to those components of the ambient magnetic field having "B

35   fields" parallel to the direction of propagation of waves

34

W1, W2. The magnetic field components produce a phenomenon, commonly known as the Faraday effect, which causes the direction of polarization for each wave to be roatated. This will be referred to herein as "Faraday

5   rotation". Assuming the polarization of the light wave is expressed as the resultant sum of two circularly polarized, counter rotating components, propagating in respective polarization modes, the magnetic field may be considered to induce such Faraday rotation by retarding

10 the propagation velocity of light in one of the polarization modes, while advancing the other by the same amount.

The polarization of a light wave may be characterized by its degree of ellipticity. If the

15 degree of ellipticity is zero, the polarization is commonly referred to as "linear". In this state, there will be equal amounts of light in each of the modes. Similarly, if the degree of ellipticity is one, the polarization may be referred to as "circular", and all

20 of the light will be in one of the modes. Further, if the degree of ellipticity is between zero and one, the polarization may be referred to as "elliptical" and the modes will have unequal amounts of light.

When the polarization of a wave is linear, the

25 differential change on propagation velocity of the polarization modes, resulting from the Faraday effect, has no effect on the phase of the wave. However, when the polarization of a wave is something other than linear (i.e., elliptical or circular), the differential

30 change in propagation velocity causes the phase of the wave to be shifted, the amount of such phase shift being dependent upon the degree of ellipticity of the polarization. This occurs because, when the polarization is circular or elliptical, there are, as

35 mentioned above, unequal amounts of light in each of the

35

two polarization modes, and thus, if the propagation velocity of one of the modes is advanced, while the other is retarded, the net effect will be to increase or decrease the propagation velocity of the wave, thereby

5 causing the phase of the wave to be shifted. Assuming, for example, that the Faraday effect increases the propagation velocity for a first mode and decreases it for a second mode, and further assuming that the light in the first mode has an amplitude larger than that of

10 the second mode, the Faraday effect will result in a leading phase shift. On the other hand, if it is assumed that the light in the second mode has a greater amplitude than the first mode, the Faraday effect will result in a lagging phase.

15   As indicated above, the phase shifts resulting from the Faraday effect may be eliminated by maintaining linear polarization for the waves W1, W2 as they counter-propagate through the loop 14. Unfortunately, however, this is difficult to accomplish, since

20 presently available optical fibers have residual linear birefrigence, which causes the waves W1, W2 to change their respective states of polarization as they propagate through the fiber. For example, if the waves W1, W2 are linearly polarized wave when introduced into

25 the loop 14, such residual linear birefrigence will cause their polarization to change, e.g., to elliptical, as the waves traverse the loop 14. Thus, each wave W1, W2 will exhibit a phase shift, due to the Faraday effect, upon exiting the loop 14. Further, in the

30 emobdiment of Figure 1, these phase shifts are in opposite directions, and thus, they produce a phase difference between the waves W1, W2.

The foregoing may be understood more fully through reference to an example. Accordingly, there is shown in

35 Figure 11 the loop portion of the rotation sensor of

36

Figure 1 which, in order to simplify the present
discussion, is illustrated as being a single turn loop,
rather than a multi-turn loop. Further, the residual
linear birefrigence of the fiber is assumed to be
5   concentrated at the center of the loop 14, at the point
designated by the reference numeral 117. Additionally,
the earth's magnetic field (B field) is assumed to be in
the plane of the loop, in the direction illustrated by
the arrows 118, so that this B field is generally
10 parallel to the fiber at the top and bottom of the loop,
as viewed in Figure 11. It will be recalled from the
discussion in reference to Figure 1 that the waves W1,
W2 are linearly polarized when they enter the loop 14,
and that the polarization controller 36 is adjusted to
15 compensate for the fiber birefrigence so that the
polarization of the waves W1, W2 is also linear when
they exit the loop 14. Furthermore, to the extent that
the fiber birefrigence is symmetrically distributed
about the loop 14, as is the case in Figure 11, the
20 polarization of the waves W1, W2, with the controller 36
so adjusted, will be the same at any given point on the
loop 14. In the present example, the birefrigence at
the center of the loop 117 will be assumed to change the
phase of each wave by one-quarter wavelength, so that
25 linearly polarized light will be transformed into
circularly polarized light, and vice versa. Thus, the
controller 36 is adjusted to compensate for this phase
change by shifting the phase an equal amount, i.e.,
one-quarter wavelength.
30   When the linearly polarized wave W1 begins its
traverse of the loop 14, the birefringence of the
controller 36 will change its state of polarization to
e.g., right-hand circular. As this wave, W1 propagates
through the top portion of the loop 14, its phase will
35 be shifted, in accordance with the Faraday effect, due

37

to the presence of the field 118. Upon reaching the
residual birefrigence at the center 117 of the loop 14,
the circular polarization of the wave W1 will be
transformed to a linear polarization. Since the

5   polarization of the wave W1 remains linear through the
bottom portion of the loop 14, the field 118 will have
no further effect on the wave W1. Similarly, the wave
W2, which intially traverses the lower portion of the
loop, is not affected by the field 118 at this lower

10   portion, since its polarization will remain linear until
it reaches the birefrigence at the point 117. At the
point 117, the polarization of the wave W2 is
transformed to e.g., right-hand circular, and thus, as
the wave W2 traverses the upper portion of the loop, its

15   phase will be shifted, in accordance with the Faraday
effect, due to the presence of the field 118. However,
since the waves W1, W2 propagate in opposite directions
with the same polarization through the upper portion of
the loop 14, but the field 118 remains in the same

20   direction, the respective phase shifts of the waves W1,
W2 induced by the field 118 will be in opposite
directions. Thus, there will be a phase difference
between the waves W1, W2 when they reach the coupler 34,
due to the Faraday effect. It may be seen, therefore,

25   that ambient magnetic fields are a source of
non-reciprocal behavior in fiber optic rotation sensors.

     In order to eliminate rotation sensing errors
produced by ambient magnetic fields through the Faraday
effect, the present invention includes a housing 110,

30   shown in Figure 12, for shielding or isolating the
rotation sensor, particularly the loop 14 and coupler
34, from such ambient fields. In the embodiment shown,
the housing 110 comprises a cylindrical tube of μ-metal
which has a sufficiently high magnetic permeability to

35   effectively shield the rotation sensor from the magnetic

environment. The dimensions of the housing 110 may be
chosen to accommodate the structural dimensions of the
rotation sensor and the hostility of the magnetic
environment. By way of specific example, the
5 μ-metal shield may be 7 inches in diameter, 18 inches
long, and 1/16th inch thick. In any case, the
dimensions and materials utilized should preferably
reduce the magnetic field impinging upon the fiber by an
amount commensurate with the sensing accuracy of the
10 rotation sensor. That is, the reduction in the magnetic
field intensity should be sufficient so that rotation
sensing accuracy is not limited by the Faraday effect
produced by such field. Assuming that the magnetic
environment is due solely to the earth's magnetic field
15 (i.e., about 0.5 gauss), the above-described embodiment
of the shield will reduce the magnetic field by a factor
of about 100 to about 0.005 gauss, which is needed to
achieve a long term stability of about 0.1 degrees/hour.

The fiber optic components of the rotation sensor,
20 including the loop 14, may be mounted on a base plate
112, mounted within the housing 110. The ends of the
housing may be closed by means of μ-metal caps 114, one
of which has a suitable opening 116 for passage of the
amplifier line 48 and modulator line 39 (Figure 1).

25 Isolating the Source 10 From the Optical Output Signal

It will be recalled from the discussion in reference
to Figure 1 that a portion of the input light from the
source 10 is coupled, by the coupler 26, to the fiber
28, where it is lost at the non-reflective termination
30 labeled "NC". Further, when the waves W1, W2 return
from the loop 14, and are combined to form an optical
output signal, a portion of this signal is lost, through
port C of the coupler 24. The remaining portion of the
output signal propagates back toward the source 10,
35 where a portion of the optical output signal is coupled,

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by the coupler 26, from the fiber 12 to the fiber 28 for propagation to the photodetector 30. The remaining uncoupled portion of the optical output signal, which propagates through the fiber 12 to the laser source 10,

5 is lost. Assuming the couplers 26 and 34 have a coupling efficiency of 50%, the system losses resulting fom the couplers 26, 34 are 87.5%. The coupler 26 alone accounts for 67.5% of this loss in optical power.

In order to reduce these system losses, the present
10. invention includes a fiber optic isolator 120, positioned between the source 10 and polarization controller 24, as shown in Figure 13. This isolator 120 comprises a polarizer 122 and a magneto-optic, or Faraday, rotator 124. In this embodiment, the need for
15 the coupler 26 (Figure 1) is eliminated by positioning the detector 30 to measure the intensity of the light rejcted by the polarizer 122. This light may be focused upon the photodetector 30 by means of a lens 126.

The operation of the fiber optic isolator may be
20 more fully understood through reference to Figures 14 and 15. Referring first to Figure 14, the polarization of the light passed by the polarizer 122 is matched to that produced by the light source 10, so that all of the source light introduced into the fiber 12 passes through
25 the polarizer 122 to the magneto-optic rotator 124. It will be understood, however, that this polarization match may be accomplished by means of a polarization controller of the type discussed above in reference to the controllers 24, 36. For the purposes of this
30 discussion, it will be assumed that the light produced by the source 10 is linearly polarized in a vertical direction, and that the polarizer 122 passes this polarization, while rejecting other polarizations. This linearly polarized light is represented in Figure 14 by
35 the arrows labeled WS.

As seen from Figure 14, the source light WS produced
by the source 10 is unchanged in polarization as it
propagates through the polarizer 122. However, when the
light passes through the rotator 124, its direction of
5 polarization is rotated by 45 degrees. Referring back
to Figure 13, the light WS then propagates through the
polarization controller 24, where its polarization is
adjusted for efficient passage through the polarizer 32,
as discussed previously. For example, if the polarizer
10 32 is designed to pass light having a linear, vertical
polarization, the controller 24 should be adjusted to
rotate the direction of polarization by 45 degrees, in a
direction opposite that produced by the rotator 124, so
that the light is again vertically polarized. The light
15 is then split into the counter-propagating waves W1, W2
by the coupler 34, for propagation about the loop 14.
After traversing the loop 14, the waves W1, W2 are
recombined, by the coupler 34, to form the optical
output signal, which propagates back through the
20 polarizer 32. It will be recalled that the polarization
controller 36 may be utilized to adjust the polarization
of the counter-propagating waves so that the optical
output signal passes efficiently through the polarizer
32, e.g., with a linear, vertical polarization. The
25 polarization controller 24, being a reciprocal device,
then rotates the direction of polarization of the
optical output signal by 45 degrees so that it now has
the same polarization upon exiting the controller 24 as
the source light did when it entered the controller 24.
30 Accordingly, as shown in Figure 15, the optical output
signal, labeled WO, is shown as entering the isolator
120 with a polarization that is identical, from the
point of view of an observer, to the polarization of the
source light WS (Figure 14) exiting the isolator 120.
35 When the optical output signal WO passes through the

rotator 124, the direction of polarization is rotated by another 45 degrees. It is a unique feature of the rotator 124 that the direction of rotation is the same regardless of the direction of propagation of the

5   light. Thus, the first 45-degree rotation of the source light and the second 45-degree rotation of the optical output signal will add so that the optical output signal WO has a horizontal direction of polarization when it leaves the rotator 124. Since the polarizer 122 rejects

10 polarizations which are orthogonal to those that it passes, the optical output signal WO will be prevented from propagating through the polarizer 122 to the light source 10. The polarizer 122 couples light from the fiber 12, so that the signal WO will be emitted from the

15 polarizer 122 in a directional, diverging beam. Preferably, the polarizer 122 is of the same type as discussed above in reference to the polarizer 32. It is significant that the light rejected by this type of polarizer is emitted therefrom in a directional ray,

20 having a relatively low divergence angle (e.g., 20°), and thus, the photo- sensitive surface of the detector 30 does not need to be especially large or uniquely shaped. In the embodiment shown, this photo-sensitive surface is about 1mm in diameter.

25   The light may be impressed upon the detector 30 by focusing it thereon, utilizing the lens 126, as discussed above. Alternatively, an optical fiber (not shown) having a core diameter of, e.g., 500 microns, may be utilized to guide the light to the detector 30, by

30 positioning one end of the fiber immediately adjacent to the polarizer so that the light rejected by the polarizer is introduced into the fiber, and by positioning the other end of the fiber so that light from the fiber is impressed upon the detector 30. It

35 should be noted that, even if all of the light rejected

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by the polarizer 122 is not impressed upon the
photosensitive surface of the detector 30, e.g., due to
slight misalignment of the focussing lens or guiding
fiber, this is more than compensated by the increase in
5   the intensity of the optical output signal resulting
from elimination of the coupler 26 (Figure 1).

Further, it is also significant that, when light is
rejected by the polarizer, the orientation of the above
described directional ray, emitted from the polarizer
10 122, will be different for one direction of propagaton
than for the other. That is, for propagation in one
direction, light is emitted on one side of the polarizer
122, while, for propagation in the other direction, the
light is emitted on the opposite side of the polarizer.
15 Therefore, even if the source light polarization is not
precisely the same as that passed by the polarizer, any
source light rejected by the polarizer will not be
directed towards the detector, and thus, will not
interfere with measurement of the optical output signal
20 intensity.

As shown in Figure 16, the magneto-optic rotator
comprises a fiber 132 wrapped upon a mandrel 170 to
provide a series of fiber loops having curved portions
and straight portions. The mandrel 170 is made from a
25 nonferrous material, such as aluminum, and comprises a
central bar portion 172, square in cross-section. A
pair of cylindrical portions 174, 176 are formed at the
respective ends of the central portion 172, and
perpendicular thereto. The cylindrical portions 174,
30 176 are oriented so that they are mutually
perpendicular. As viewed in Figure 16, the cylindrical
portion 174 has a right end 175 (a) and left end 175
(b), projecting from respective parallel sides of the
central portion 172. Similarly, the cylindrical portion
35 176 has an upper end 177 (a) and lower end 177 (b),

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projecting from respective parallel sides of the central portion 172. Further, the cylindrical portions 174, 176 have diameters which are equal to or larger than the sides of the central portions 172.

5   The fiber 132 is first wrapped around the upper end 177a of the cylindrical portion 176 to form a curved fiber portion 178 joining two straight portions 180, 182. Next, the fiber is wrapped around the left end 175b of the horizontal cylindrical portion 174 to form a

10   curved portion 183 joining the straight portion 182 with a straight portion 184. The wrapping continues by forming another curved portion 186 around the lower end 177b of the vertical cylindrical portion 176 to join the sraight portion 184 to a straight portion 188. Finally,

15   another curved portion 190 is formed, by wrapping the fiber 132 around the right end 175b of the horizontal portion 174 to join the straight portion 188 with a straight portion 192. It will be understood that the wrapping is accomplished so that the straight portions

20   180, 182, 184, 188 and 192 are parallel to each other. Further, by wrapping the fiber in the foregoing manner, the curved portions 178, 186 will lie in a horizontal plane, while the curved portions 183, 190 lie in a vertical plane.

25   Although, for clarity of illustration, only four turns (curved portions) are provided in the fiber 132 of Figure 16, it will be understood that the fiber 132 may be wrapped in the same manner to provide additional turns. In addition, it will be understood from the

30   following description that, although the curved portions are shown to comprise 1/2 turn, they may comprise N + 1/2 turns (n being an integer) and still permit the straight portions to be positioned as shown in Figure 16.

      A magnetic field is applied to the fiber 132 by

35   positioning the mandrel 170 between the poles of a

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magnet 200, as shown in Figure 17, so that the B field
of this magnet is parallel to the straight portions of
the fiber 132. The magnet 200 may be of any suitable
type or shape. For example, it may be either an
5   electro-magnet or permanent magnet. Further, the magnet
may be e.g., shaped as a toroid, or as a horseshoe.

As light propagates through these straight portions
80, 82, 84, 88 and 92, its direction of polarization is
rotated by the magnetic field, in accordance with the
10   Faraday effect. With the fiber 132 wrapped in the
manner shown in Figure 16, light propagating through the
fiber 132 reverses its direction of propagation as it
travels from one straight portion to another straight
portion. Thus, it will propagate in the same direction
15   as the B field, e.g., through the straight portions 180,
184 and 192, but will propagate in the opposite
direction from the B field through, e.g., the straight
portions 182 and 188. The magnetic field, therefore,
will rotate the polarization, in accordance with the
20   Faraday effect, so that, from the viewpoint of a fixed
(i.e., stationary) observer, the Faraday rotations in
any two adjacent straight portions 178, 183, 186, 190,
will appear to be in the same direction. However, even
though these rotations are in the same direction, they
25   do not ordinarily add to each other since, due to
propagation around the curved portions 178, 183, 186,
190, the direction of polarization (as viewed by a
stationary observer) in one straight portion is reversed
so that it is the mirror image of the light in an
30   adjacent straight portion, and thus, the rotations due
to the Faraday effect in any two adjacent straight
portions would cancel, yielding a net rotation of zero.
The magneto-optic rotator of Figure 16 solves this
problem by forming the curved portions 178, 183, 186,
35   190 (i.e., selecting the diameter of the cylindrical

portions 174, 176 and the number of turns of the fiber
132) so that they each create a linear birefringence
sufficient to provide a spatial separation between light
in the polarization modes of one-half wavelength, or a
5   phase difference of 180 degrees. This advantageously
causes the direction of polarization as viewed by an
observer to be the same in each of the straight portions
180, 182, 184, 188, 192, so that the Faraday rotations
add to each other, rather than cancel each other. Thus,
10   by providing a series of straight portions, a large
Faraday rotation may be obtained, even though the
Faraday rotation for one of the straight portions may be
relatively small.

If the strength of the magnetic field (B field)
15   applied to the fiber 132 is approximately 1,000 gauss, a
fiber wrapped according to the specifications set forth
below will provide a total Faraday rotation of 45
degrees for light propagating through the fiber in
either direction. Thus, if a lightwave propagates
20   through the fiber 132 in one direction, and returns
therethrough in the other direction, the total Faraday
rotation will be 90 degrees. This amount of Faraday
rotation permits the magneto-optic rotator to be
utilized as an optical isolator, in the manner discussed
25   in reference to Figures 14 and 15.

For example, in one embodiment, which has been
constructed, a total of 32 turns are utilized. The
specifications for this embodiment are as follows:

Number of curved portions:	32
Number of straight portions:	33
Length of one straight portion:	12 cm
Diameter of mandrel cylindrical portion:	2.5 cm
Number of turns for each curved portion:	1.5
Outside diameter of the fiber:	110 microns
Wavelength of the light:	0.633 microns
Total length of fiber:	4 meters
	(approx.)

CLAIMS:

1. A fiber optic system for sensing rotation, characterized in that said system comprises:

    a light source (10);

5   a loop (14) of fiber optic material which transmits light in a single mode from said light source (10);

    an evanescent field fiber optic directional coupler (34), connected between said light source

10 (10) and said loop (14), for splitting light from said source (10) into two waves which propagate around the loop (14) in opposite directions; and

    detector means (30) responsive to the phases of said two waves for providing an output signal

15 corresponding to rotation of said loop (14).

2. A rotation sensor as claimed in Claim 1, further characterized by comprising:

    an optical isolator (120), positioned between the light source (110) and the coupler (34) for

20 allowing passage of light from said source (34) to said loop (14), while preventing passage of light from said loop (14) to said source (10).

3. A rotation sensor as claimed in Claim 1 further characterized in that the light is transmitted to the

25 coupler (34) from the source (10) over a fiber optic line (12), the coupler (34) recombines the counter propagating waves and delivers a combined output wave back to the line (12), and said rotation sensor further comprises means (26 or 120), connected between the

30 coupler (34) and the light source (10), for coupling the output wave from the line to the detector means (30).

4. A rotation sensor as claimed in Claim 3, further characterized in that said means for coupling comprises a second evanescent field fiber optic directional

35 coupler (26).

5. A rotation sensor as claimed in Claim 3, further
characterized in that said means for coupling comprises
an optical isolator (120) which passes light from said
source (10) to said loop (14), but couples said combined
5   output wave from said line (12) to prevent it from
reaching said source (10).

6. A rotation sensor as claimed in Claim 5,
characterized by comprising means (126) for guiding said
output wave from said isolator (120) to said detector
10 means (30).

7. A rotation sensor as claimed in Claim 6, further
characterized in that said guiding means comprises a
lens.

8. A rotation sensor as claimed in Claim 6, further
15 characterized in that said guiding means comprises an
optical fiber.

9. A rotation sensor as claimed in any of Claims 3 to
8, further further characterized in that it includes
fiber optic polarizing means (32), connected to the line
20 (12), for passing light of predetermined polarization.

10. A rotation sensor as claimed in Claim 9, further
characterized by comprising fiber optic means (24, 36)
for controlling the polarization of the light from the
source and the counter propagating waves for maximum
25 transmission by the polarizing means (32).

11. A rotation sensor as claimed in Claim 10, further
characterized in that the line (12) and the loop (14)
comprise a single, uninterrupted strand of fiber optic
material which passes continuously through the fiber
30 optic coupler (34), the coupling means (26 or 120) , the
polarizing means (32) and the polarization controlling
means (24, 36), said coupler (34), coupling means (26 or
120), polarizing means (32) and polarization controller
means (24, 36) all being formed on the strand (12) with
35 no splicing or interruption of the strand (12).

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12. A rotation sensor as claimed in any of Claims 1 to
11, further characterized in that it includes means for
reducing the coherence between the counter-propagating
waves and the backscattered light to reduce noise in the
5   system.

13. A rotation sensor as claimed in Claim 12, further
characterized in that the means for reducing the
coherence comprises a phase modulator connected to the
center of the loop (14) of fiber optic material.

10   14. A rotation sensor as claimed in any of Claims 1 to
13, further characterized in that the loop (14)
comprises a strand of fiber optic material wrapped for a
plurality of turns about a support, with the central
turns being positioned innermost adjacent to the support
15   and the turns toward the ends of the loop being
positioned outermost away from the support so that both
end portions of the strand forming the loop are
positioned symmetrically about the central turns and are
freely accessible at the outside of the loop.

20   15. A rotation sensor as claimed in any of Claims 1 to
14, characterized by comprising means for modulating
(38) the phase of the two waves at a specific frequency,
the modulating means (38) separated from the coupler
(34) by a fiber length in one direction of said loop
25   which is a length L different from the fiber length
between the modulating means (38) and the coupler (34)
in the opposite direction of said loop (14), said
modulating means introducing an amplitude modulation in
at least one of said two waves, said specific frequency
30   selected to eliminate errors caused by said amplitude
modulation at the detector means (30).

16. A rotation sensor as claimed in Claim 15, further characterized in that said specific frequency equals C/2NL, where L is said length L, C is the free space velocity of light, and N is the equivalent refractive

5 index for said fiber optic material.

17. A rotation sensor as claimed in Claim 15 or 16, further characterized in that said amplitude modulation is caused directly by said means (38) for modulating the phase.

10. 18. A rotation sensor as claimed in Claim 15 or 16, further characterized in that said amplitude modulation is caused by polarization modulation introduced by said means (38) for modulating the phase.

19. A rotation sensor as claimed in any of Claims 15 to

15 18, further characterized in that the coupler (34) recombines the waves after propagation about the loop (14) to provide a combined light wave, and the detector means (30, 46) detects only an odd harmonic of said combined wave, and wherein said specific frequency

20 causes the odd harmonic frequency components of said amplitude modulation to cancel when the waves are recombined by the coupler (34).

20. A rotation sensor as claimed in Claim 19, further characterized in that said detector means (30, 46)

25 detects only the fundamental frequency of said combined wave.

21. A rotation sensor as claimed in any of Claims 15-20, further characterized in that said detector means (30, 46) comprises an amplifier (46) providing a narrow

30 bandpass filter characteristic at said specific frequency.

22. A rotation sensor as claimed in Claim 21, further characterized in that said detector means (30, 46) comprises a lock-in amplifier (46) synchronized to said

35 means (38) for modulating.

23. A rotation sensor as claimed in any of Claims 15-22, further characterized in that said specific frequency is selected, with reference to said Length L, to provide a modulation phase difference of 180 degrees in said two
5 waves upon recombination at said coupler (34).

24. A rotation sensor as claimed in any of Claims 1 to 23, further characterized by comprising means (110) for shielding the loop (14) of fiber optic material from an ambient magnetic field to reduce the effects of the
10 magnetic field on the light waves in said loop.

25. A rotation sensor as claimed in Claim 24, further characterized in that the shielding means (110) reduces the intensity of the magnetic field at said loop (14) by an amount sufficient to prevent its effect upon the
15 light waves in said loop (14) from limiting the sensing accuracy of the rotation sensor.

26. A rotation sensor as claimed in Claim 24 or 25, further characterized in that said shielding means (110) comprises a housing (110) for said loop (114), the
20 housing (110) made from a magnetically permeable material.

27. A method of increasing the rotation sensing accuracy of a rotation sensor, characterized by comprising utilizing a sensor as defined in any of Claims 1-23 and
25 shielding the sensing loop (14) from ambient magnetic fields.

28. A method of sensing rotation characterized by comprising using a sensor as defined in any of Claims 1-26 to sense rotation.
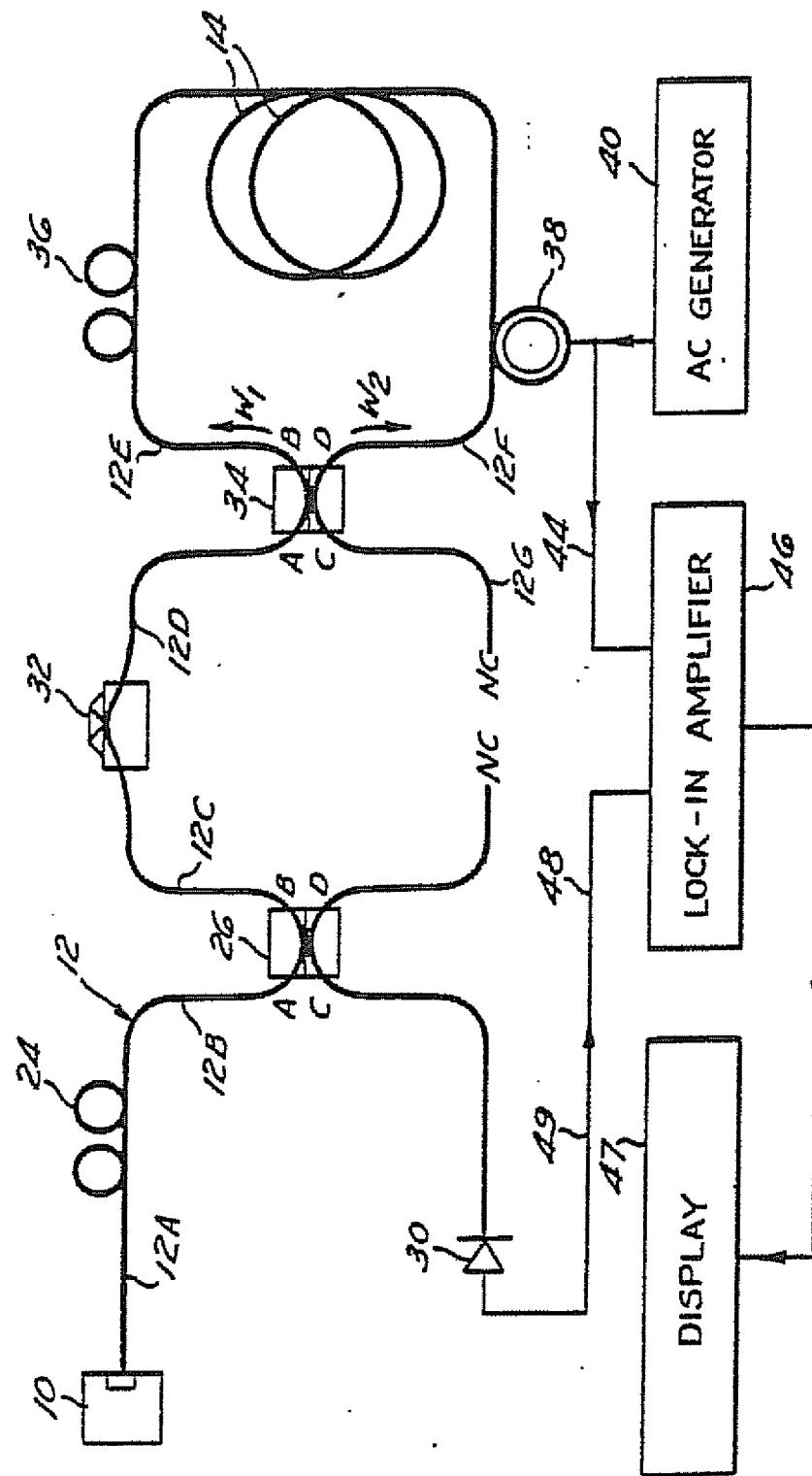
Fig. 1

Fig. 2
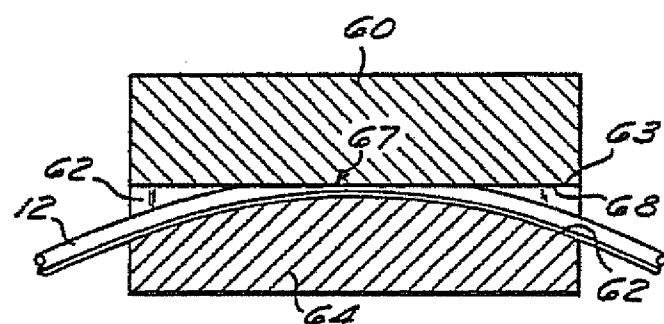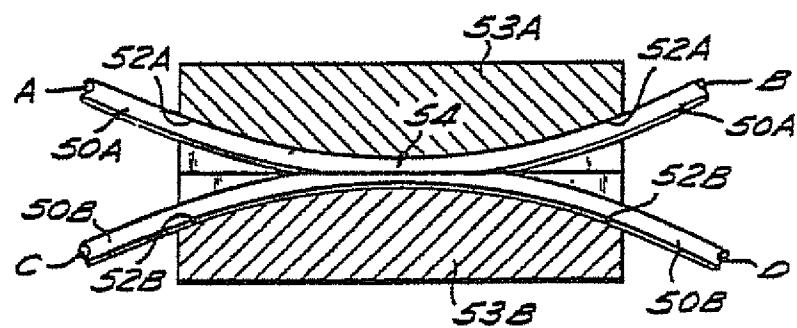
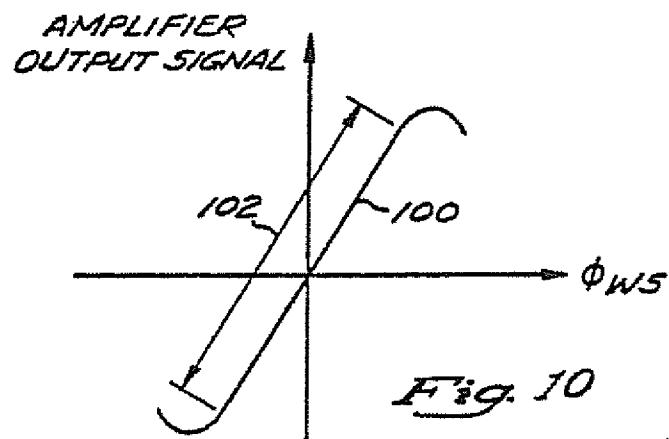

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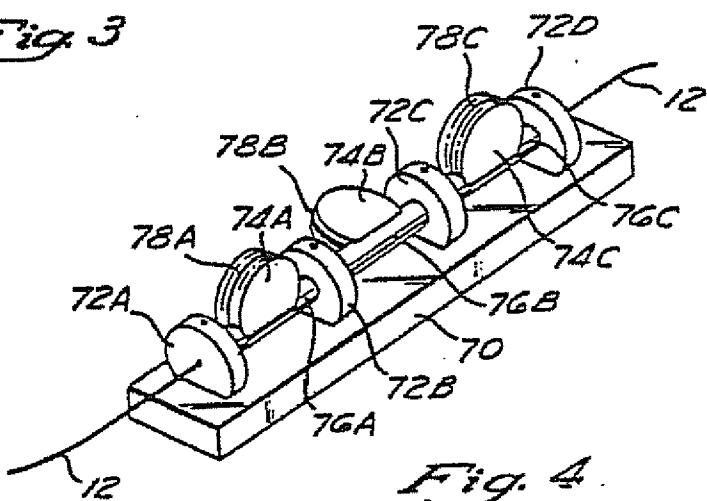
Fig. 4

Fig. 5
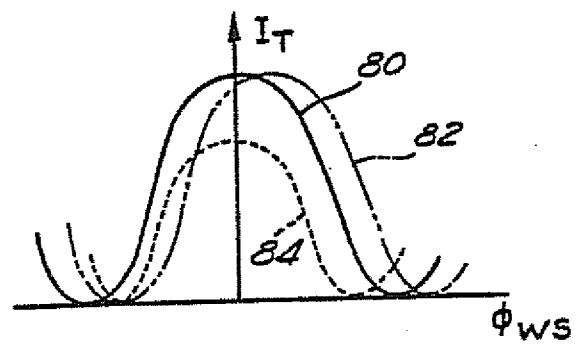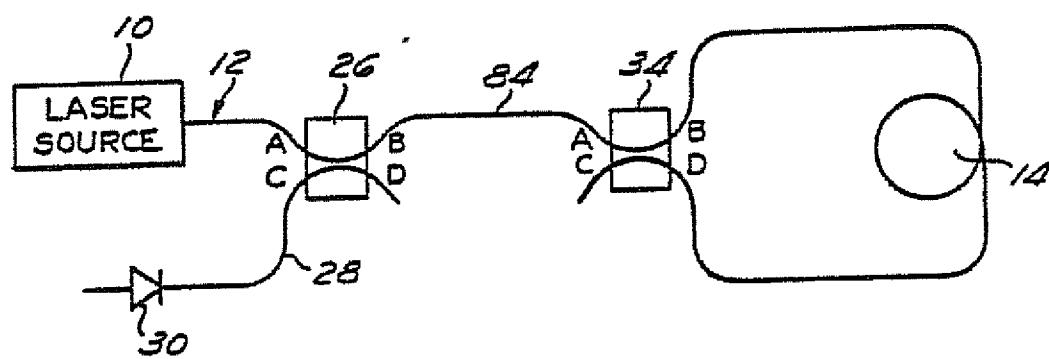
Fig. 6
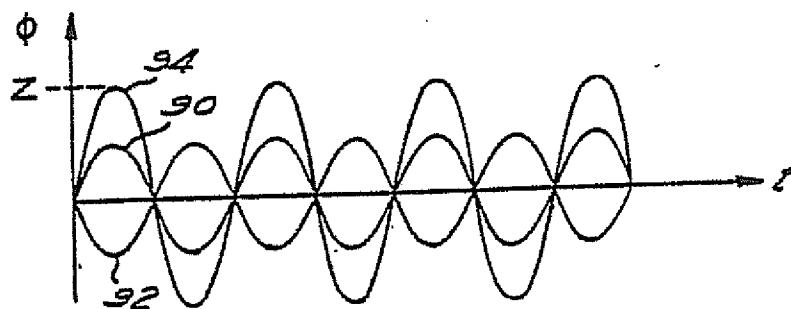
Fig. 7
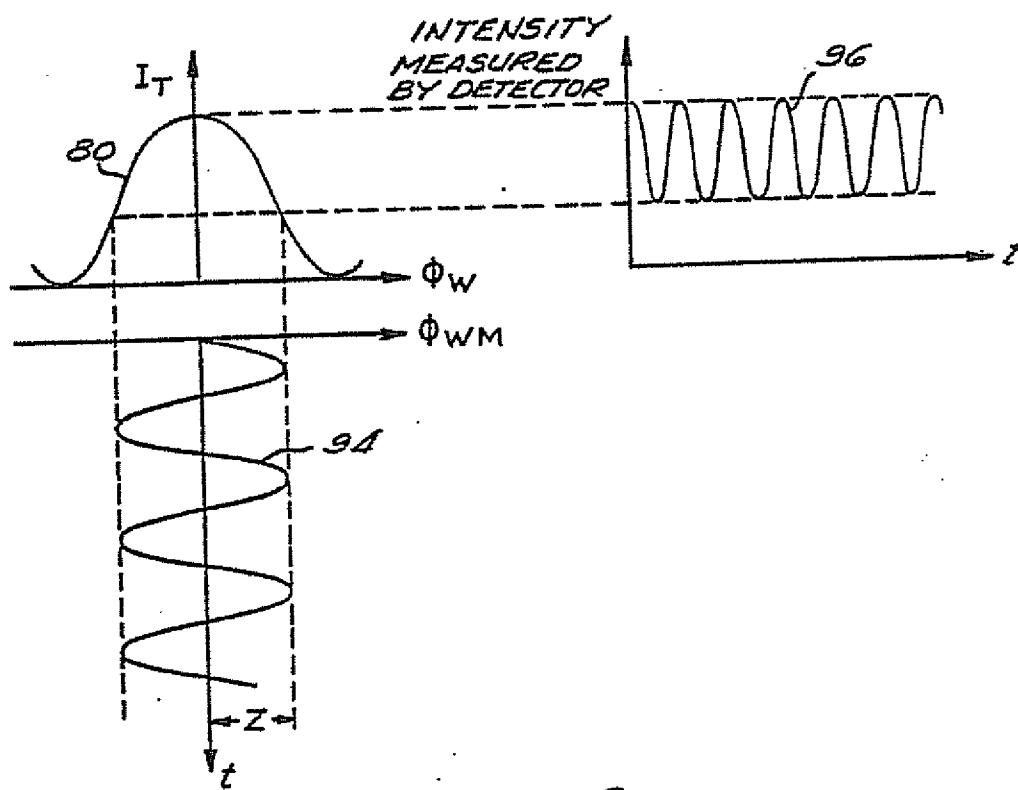
Fig. 8
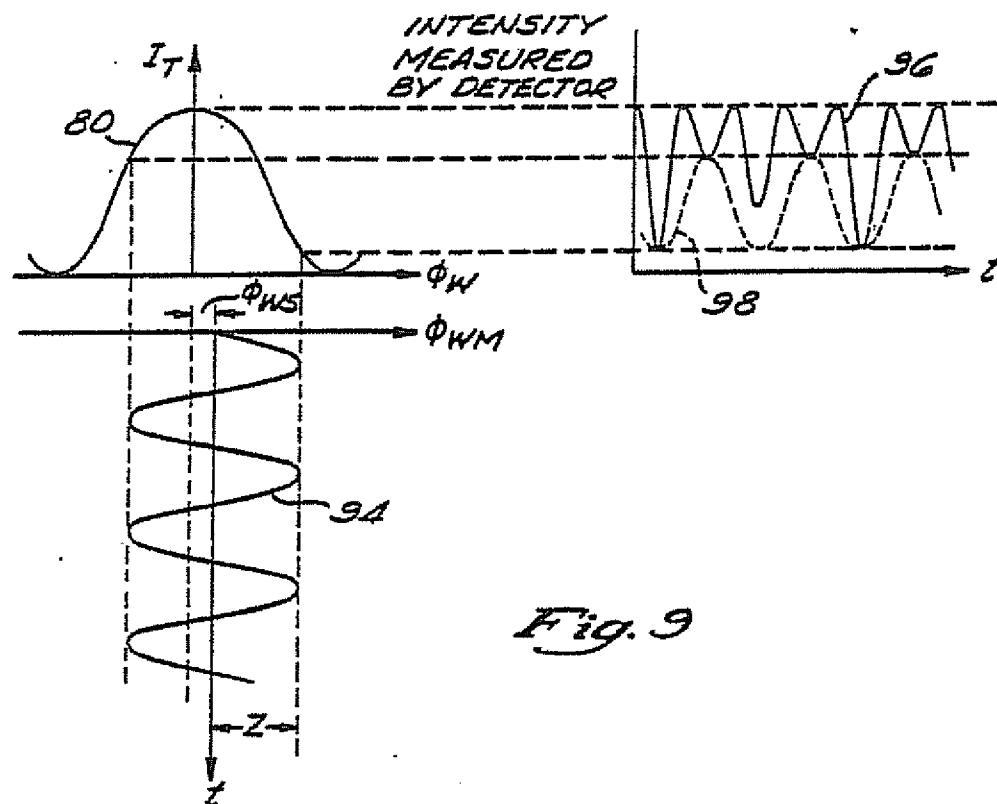
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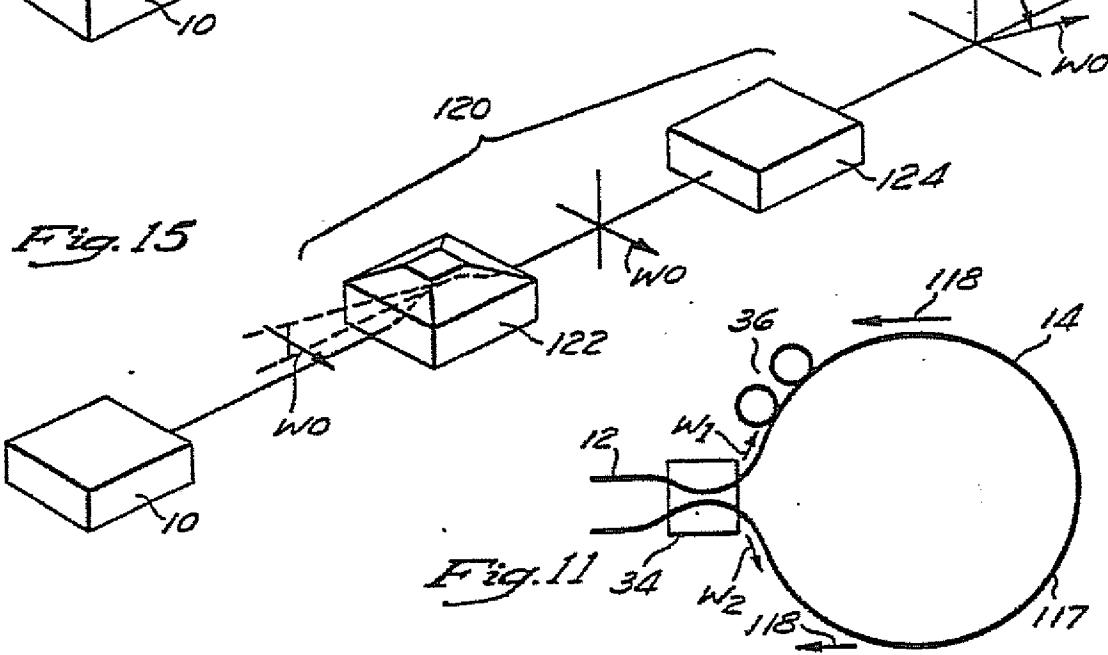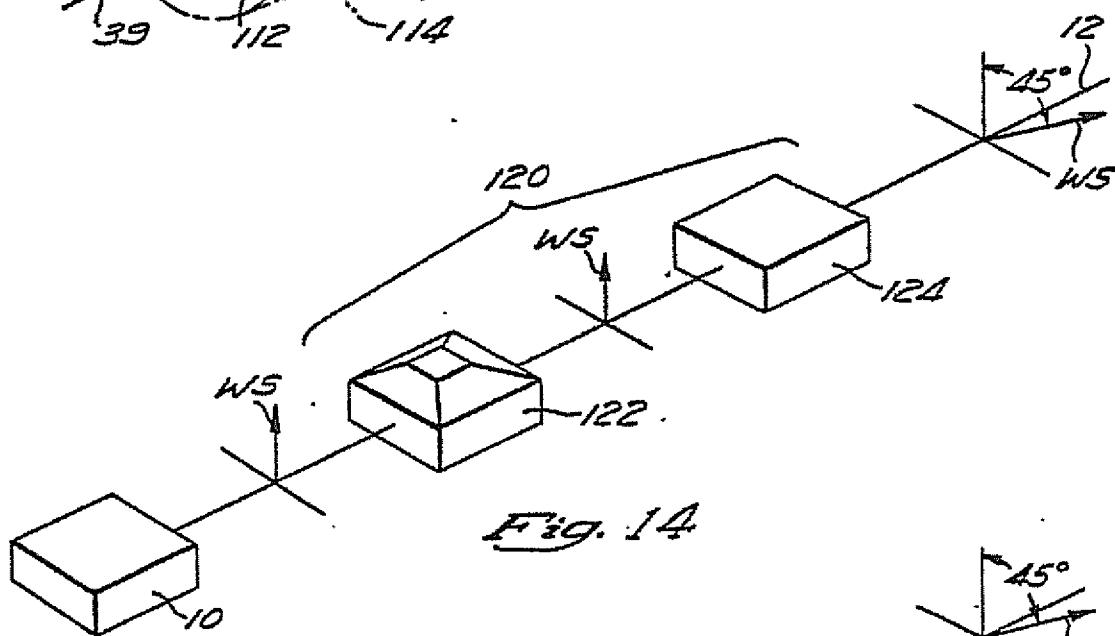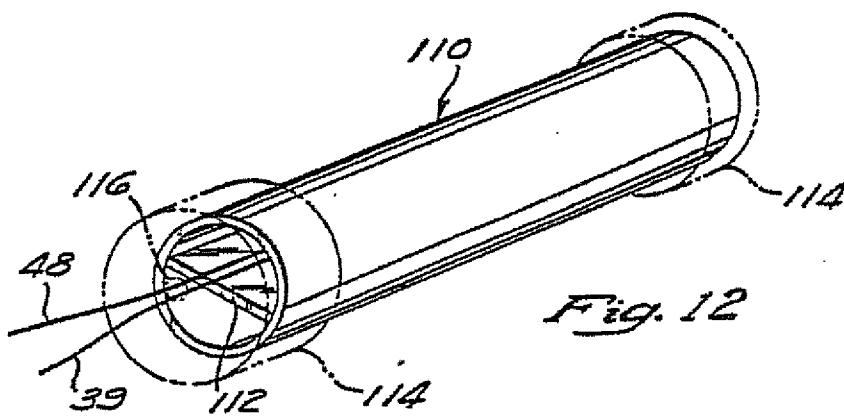
Fig. 9

Fig. 10
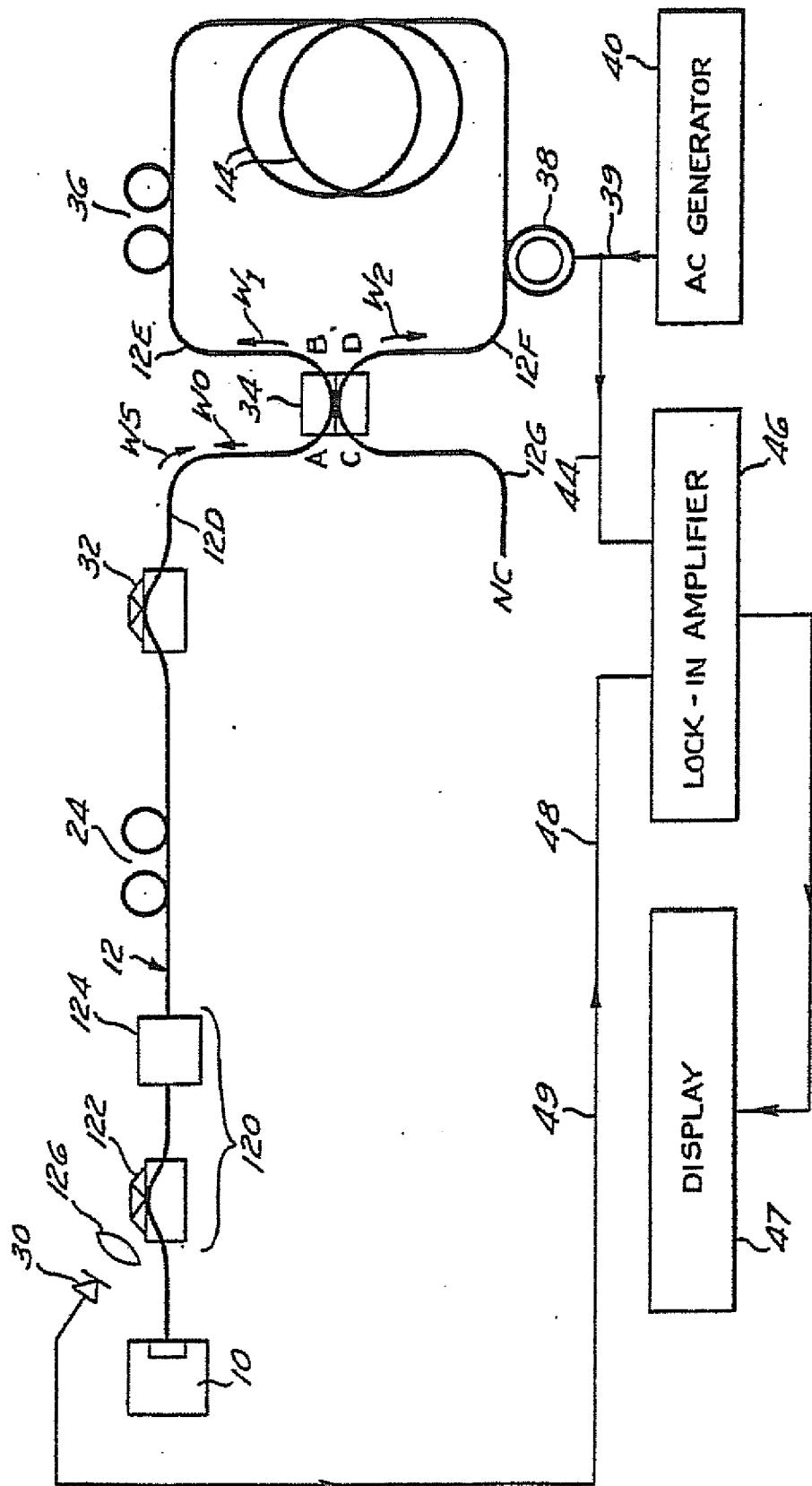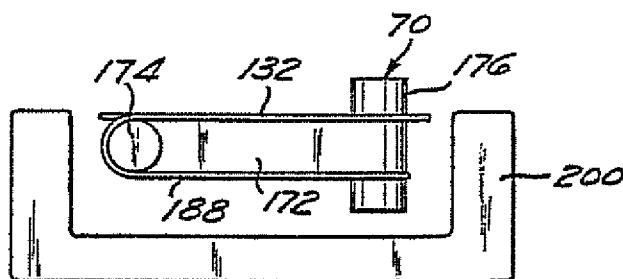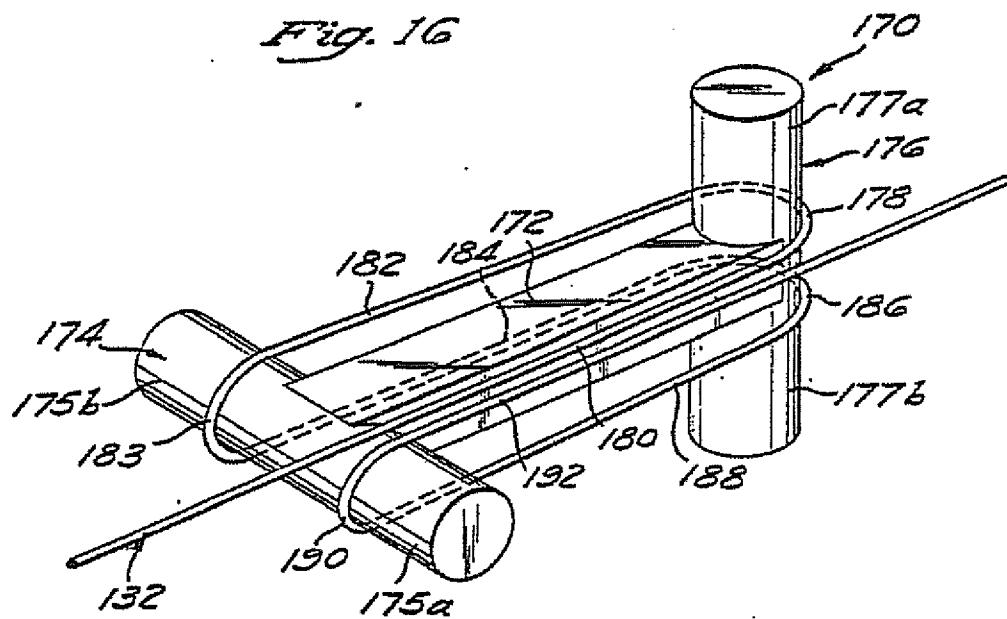
Fig. 12

Fig. 14

Fig. 15

Fig. 11

BUREAU
OMPI
WIPO

Fig. 13

Fig. 16

Fig. 17

SUBSTITUTE SHEET

INTERNATIONAL SEARCH REPORT

International Application No PCT/US82/00400

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) ³

According to International Patent Classification (IPC) or to both National Classification and IPC

INT. CL.³ G01C 19/64, G01B 9/02
U.S. CL. 356/350, 351

II. FIELDS SEARCHED

Minimum Documentation Searched ⁴

Classification System	Classification Symbols
U.S.	356/350, 351

Documentation Searched other than Minimum Documentation to the Extent that such Documents are included in the Fields Searched ⁵

III. DOCUMENTS CONSIDERED TO BE RELEVANT ¹⁴

Category *	Citation of Document, ¹⁶ with indication, where appropriate, of the relevant passages ¹⁷	Relevant to Claim No. ¹⁸
X,P	US, A, 4,283,144, Published 11 August 1981, MC LANDRICH	1,3,4,14,28
X,P	US, A, 4,299,490, Published 10 November 1981, See Fig. 10, CAHILL ET AL	2,5-8
X	N, ELECTRONICS LETTERS, Volume 16, No. 20, issued 25 September 1980 (London, England) H. C. LEFEVRE 'Single-Mode Fibre Fractional Wave Devices and Polarization Controllers', pages 778-780.	9-11
X	N, OPTICS LETTERS, Volume 5, No. 5, issued May 1980 (New York, New York), R. ULRICH, 'Fiber-Optic Rotation Sensing With Low Drift', pages 173-175.	15-23
X	US, A, 3,862,803, Published 28 January 1975, See Shield 32, YNTEMA ET AL	24-27

* Special categories of cited documents: ¹⁵

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

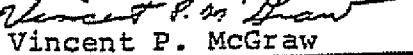| Date of the Actual Completion of the International Search ²	Date of Mailing of this International Search Report ²
7 JULY 1982	14 JUL 1982

International Searching Authority ¹	Signature of Authorized Officer ²⁰
ISA/US	Vincent P. McGraw

Form PCT/ISA/210 (second sheet) (October 1981)